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SERPENTINE DERIVED SOILS

IN

WATERSHED AND FOREST MANAGEMENT

WITH ANNOTATED BIBLIOGRAPHY

October 1970

Report to the U. S. Department of Interior
Bureau of Land Management
Contract No. 53500-CTO-420 (N)

Department of Soils
Oregon State University
Corvallis, Oregon

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From: Director, PSC

Subject: Research Report - Serpentine Derived Soils - OSU

A copy of the subject report is attached for your use and information. The literature review of serpentinitic soils (ultramafic) in the Northwest was completed recently by Oregon State University.

Edward L Byland

Enclosure (1)
Encl. - Research Report

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SERPENTINE DERIVED SOILS IN WATERSHED AND FOREST MANAGEMENT

Dhanpat Rai, Gerald H. Simonson, and Chester T. Youngberg[1/]

INTRODUCTION

The soils developed from serpentine rocks support a distinctive vegetation. The serpentine flora differ so sharply from nonserpentine flora that even a casual observer cannot help noticing the sharp differences in vegetation. Harshberger (1903) observed that serpentine flora is barren in appearance and the types of flora differ sharply from the surrounding nonserpentine areas. He described this character of serpentine flora as follows, " ... The serpentine plants taken together, therefore, form islands set down in a sea of other vegetation with a boundary as well characterized as the shore of an oceanic island, and with tension lines induced by the struggle for existence as sharply drawn as the shore line against which the storm waves beat."

Many ecologists have described the vegetation on serpentine soils which occur in different parts of the world. But very little research has been done on serpentine soils. Plants grown on serpentine soils, in general, show the following tendencies: shrubi-ness of growth, stunting or dwarfing, greater development of root system, and increased glaucousness (Pichi-Sermolli, 1948). The differences in species composition of serpentine flora of various geographic locations and climatic regions is expected. However, many research workers have observed difference

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1/ Research Associate, Associate Professor,and Professor, Department of Soils, Oregon State University, respectively.

[1] Research Associate, Associate Professor, and Professor, Department of

in species compositions and other characteristics of serpentine and nonserpentine soils floras (occurring in a given geographic location and under a similar set of climatic conditions). Rune (1953) lists the following general characteristics of serpentine flora in contrast with nonserpentine flora: poor in individuals and species, ecotypes of several species differing ecologically and morphologically, disjunctive nature of plants, xerophytic character, and dominance by certain families or genera. It is clear from the above that characteristic differences in serpentine and nonserpentine flora may be due mainly to the nature of the serpentine soils.

Some workers have observed that serpentine rocks and soils are unstable on the landsurface in addition to their infertile nature. For proper watershed and forest management, it is necessary to find out the causes of infertility and instability of the serpentine soils. It was with these aspects in mind that the present review was undertaken.

The following objectives were established for the present study.

1. Review literature on serpentine soils.
2. Compare (from limited field and laboratory data) serpentine soils in Oregon and California with serpentine soils elsewhere to determine applicability of available information to these soils in the Northwest.
3. Outline causes of infertility and instability of serpentine soils.
4. Outline future research needs and management of these soils.

SERPENTINE MINERALOGY AND COMPOSITION

Serpentine has been used as a rock name and also as a name applied to a group of minerals. Most serpentine rocks (serpentinites) are the alteration products of ultrabasic igneous rocks such as pyroxenites and peridotites. The predominant minerals in serpentine rocks are a group of serpentine minerals with remains of original olivine, pyroxene, hornblende, and small amounts of chromite, magnetite and garnet (Grout, 1940).

Serpentine as a mineral name applies to chrysotile and antigorite (Berry and Mason, 1959); chrysotile (Clino, Ortho, and Para), antigorite, and lizardite (Whittaker and Zussman, 1956); and to chrysotile (Clino, Ortho, and Para), antigorite (various a-parameters), 6 layer ortho-serpentine, and lizardite (Zussman et al., 1957).

Serpentine group minerals are 1:1 trioctahedral phyllosilicates. Until recently, these minerals were considered to be polymorphic forms with similar composition ($Si_4Mg_6O_{10}(OH)_8$). Berry and Mason (1959) indicated that some serpentine minerals may have some iron in the octahedral layer as a result of the replacement of Mg, and some Al probably through substitution for Mg in the octahedral layer and Si in the tetrahedral layer. There is a nickel bearing variety of serpentine which is called garnierite ($Si_4(Mg,Ni)_6O_{10}(OH)_8$). Deer et al. (1962) believed that antigorite is different from chrysotile and lizardite both in structure and composition and hence not a true polymorph. Page (1968) showed differences in chemical composition (by electron probe) among antigorite (low H_2O, high SiO_2, and large numbers of trivalent ions in 4-fold co-ordination), chrysotile (high H_2O and MgO, and small ratio of Fe_2O_3 to FeO), and lizardite (high SiO_2, low

FeO, and large ratio of Fe_2O_3 to FeO) indicating that these minerals are not polymorphs. The serpentine minerals are, however, at least similar in composition and in the basic arrangement of atoms in the crystal structure.

The differential thermal analysis of ground rock sample (Sample No. VIII-3, Waldo Hill, Oregon)[2/] gave an endothermic peak at 656°C and a sharp exothermic peak at 837°C (Figure 1) which indicates the presence of serpentine (possible chrysotile and/or lizardite). The random powder X-ray diffraction pattern of the above sample (Table 1) also indicated the presence of 1:1 trioctahedral mineral, serpentine, which may be chrysotile. Whether the above rock is chrysotile and/or lizardite is immaterial for the present study. Since the above rock is serpentine, it can be assumed that it has composition similar to that reported earlier for serpentine.

[2/] Description of samples collected is given in Appendix I.

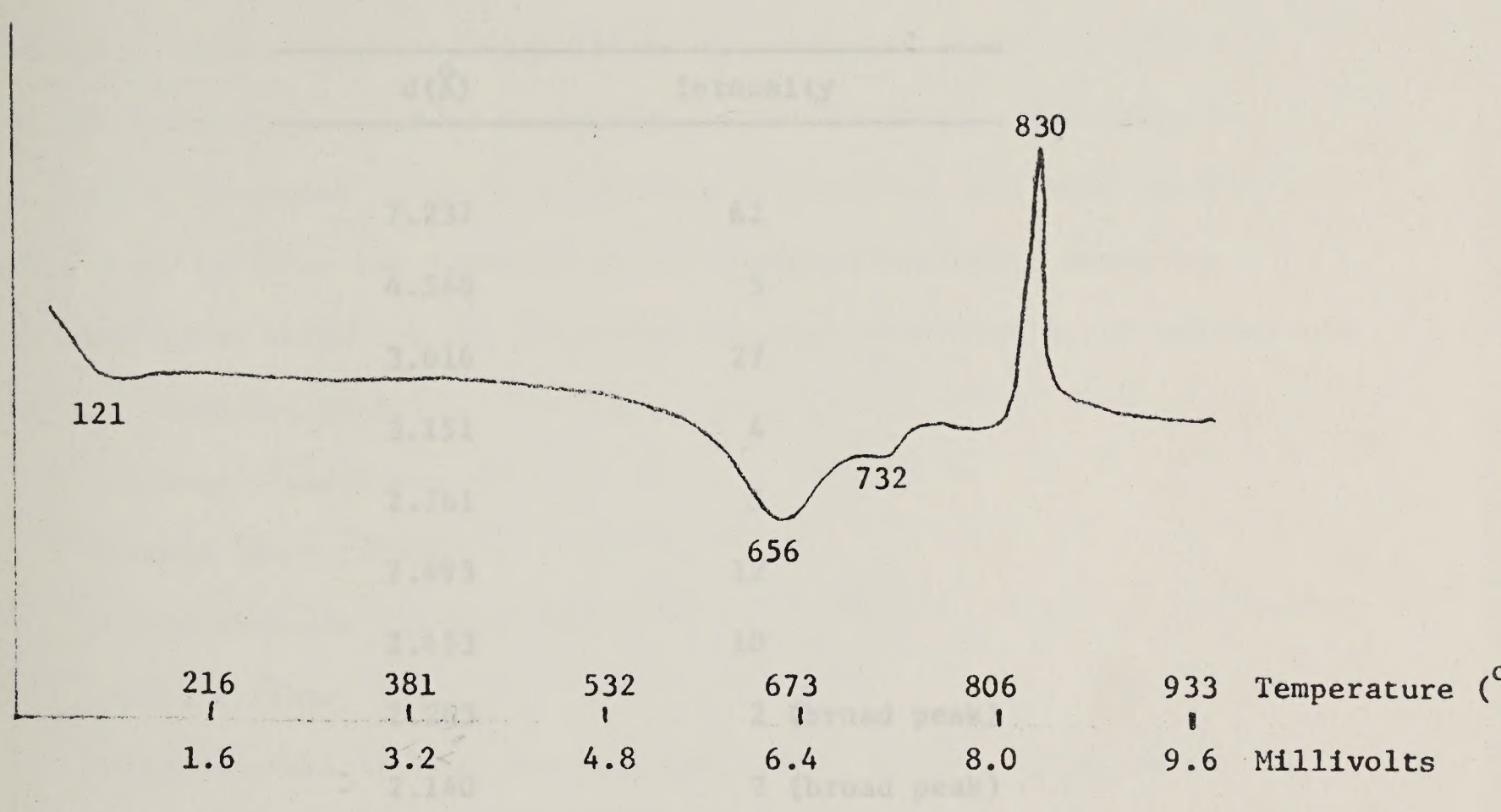

Figure 1. DTA curve for powdered serpentine rock (Waldo Hill, Oregon; Sample No. VIII-3).

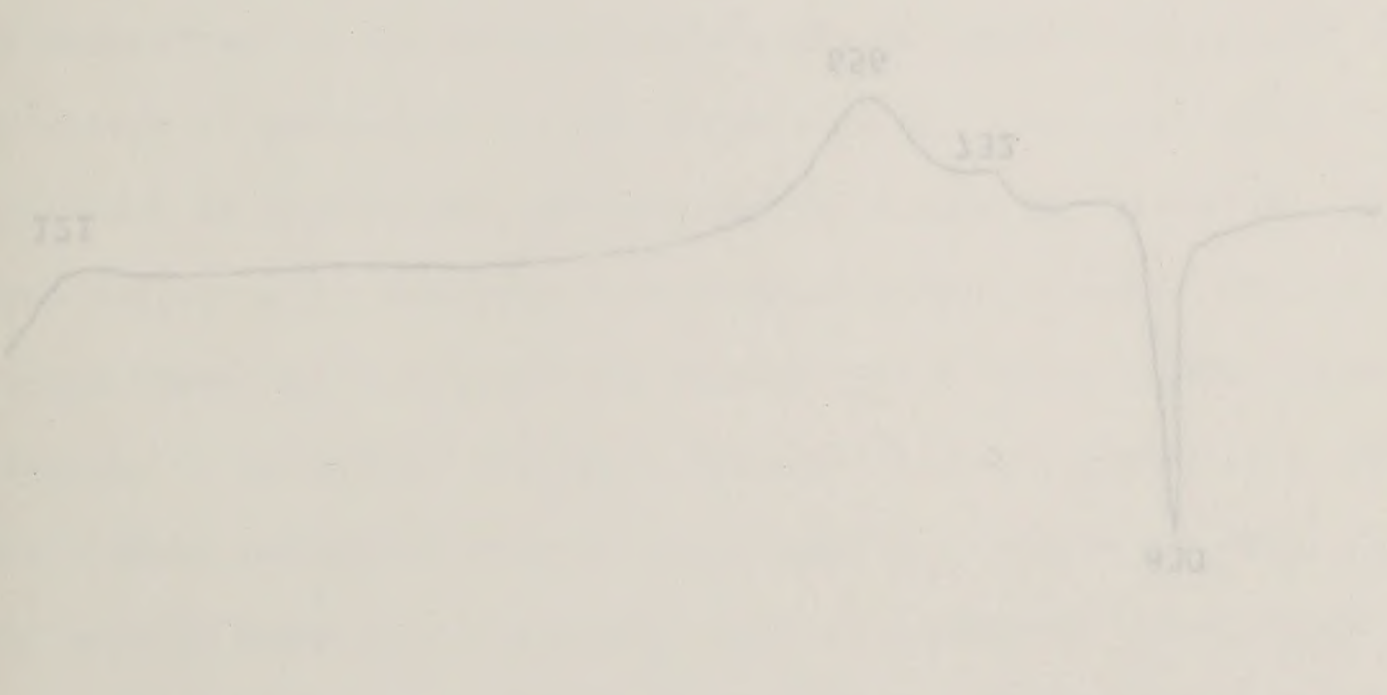

Table 1. X-ray (diffraction) powder data for serpentine rock (Waldo Hill, Oregon; Sample No. VIII-3).

d(Å)	Intensity
7.237	62
4.548	5
3.616	27
3.151	4
2.761	5
2.493	12
2.453	10
2.263	2 (broad peak)
2.140	2 (broad peak)
1.786	2 (broad peak)
1.738	4
1.536	5

OCCURRENCE OF SERPENTINE

World-Wide (Excluding U.S.)

Serpentine occurs in many areas of the world, generally in relatively small rock exposures. There have been many ecological studies on serpentine rock-soil systems because of the unusual flora of these areas. However, very little is mentioned about the extent of the serpentine areas in various parts of the world. Following is a list of countries in which serpentine occurrences have been noted. This list is in no way intended to be an exhaustive one. There may be some areas which are not mentioned here and others on which information is not available at all.

Albania (Bogatyrev, 1958)

Canada (Rune, 1953)

Czechoslovakia (Novak, 1928)

Finland (Rune, 1953)

Great Britain (Hunter and Vergnano, 1952; Butler, 1953; and Coombe and Frost, 1956a, and 1956b)

Italy (Pichi Sermolli, 1948; Malquori and Cecconi, 1956; and Venaile and Van der Marel, 1963)

Japan (Rune, 1953; Arimura and Kanno, 1965; Yatazawa and Tanaka, 1965; Yamanaka, 1959; Kanno *et al.*, 1965; Nagatsuka, 1965 and 1967; and Sasaki, 1968)

New Caledonia (Birrell and Wright, 1945)

Norway (Rune, 1953)

Philippines (Frasche, 1941)

Scotland (Vergnano, 1953a and 1953b)

Spain (Hoyos de Castro, 1960)

Sweden (Rune, 1953)

Yugoslavia (Novak, 1928).

In addition to the above countries, Whittaker (1954a) mentions the presence of serpentine in Austria, Cuba, France, Greece, Indonesia, New Zealand, Newfoundland, Puerto Rico, Switzerland, Southern Rhodesia and in the Ural Mountains.

Serpentine Occurrence in the United States

Grout (1940) mentions the presence of serpentinite outcrops scattered in the Appalachian metamorphic belt (Staten Island, Pennsylvania, Maryland, North Carolina, and Georgia), in the Lake Superior region, and in the coast ranges along the Pacific Coast.

Extensive serpentine areas are found in California, Oregon, and Washington. Most of California serpentine areas (Lipman, 1926; Kruckeberg, 1951, 1954 and 1959; McMillan, 1956; Ishimoto, 1958; Whittaker, 1960; Wells, 1962; Hotz, 1964; Wildman, 1967; Wildman et al. 1968a and 1968b; and Waring, 1969) are in Sierra Nevada and the central and north coast ranges (Figure 2). There are about 1100[3/] square miles of serpentinitic (ultramafic) areas in California.

In Oregon, most of the serpentine areas (Figure 3) (Whittaker, 1954b; Wagner and Ramp, 1958; Whittaker, 1960; Youngberg, 1964; Franklin and Dyrness, 1969; and Waring, 1969) are in the southwestern parts of the state in the Siskiyou Mountains and south coast range. Large contiguous areas of serpentine occur adjacent to California in Josephine County. There are some scattered serpentine outcrops in northeastern Oregon. There are about 450[4/] square miles of serpentinitic (ultra-

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[3/] This figure is estimated from geologic map of California, California Division of Mines. Prepared by Jenkins (1938).

[4/] This figure is estimated from maps given by Wagner and Ramp, 1958.

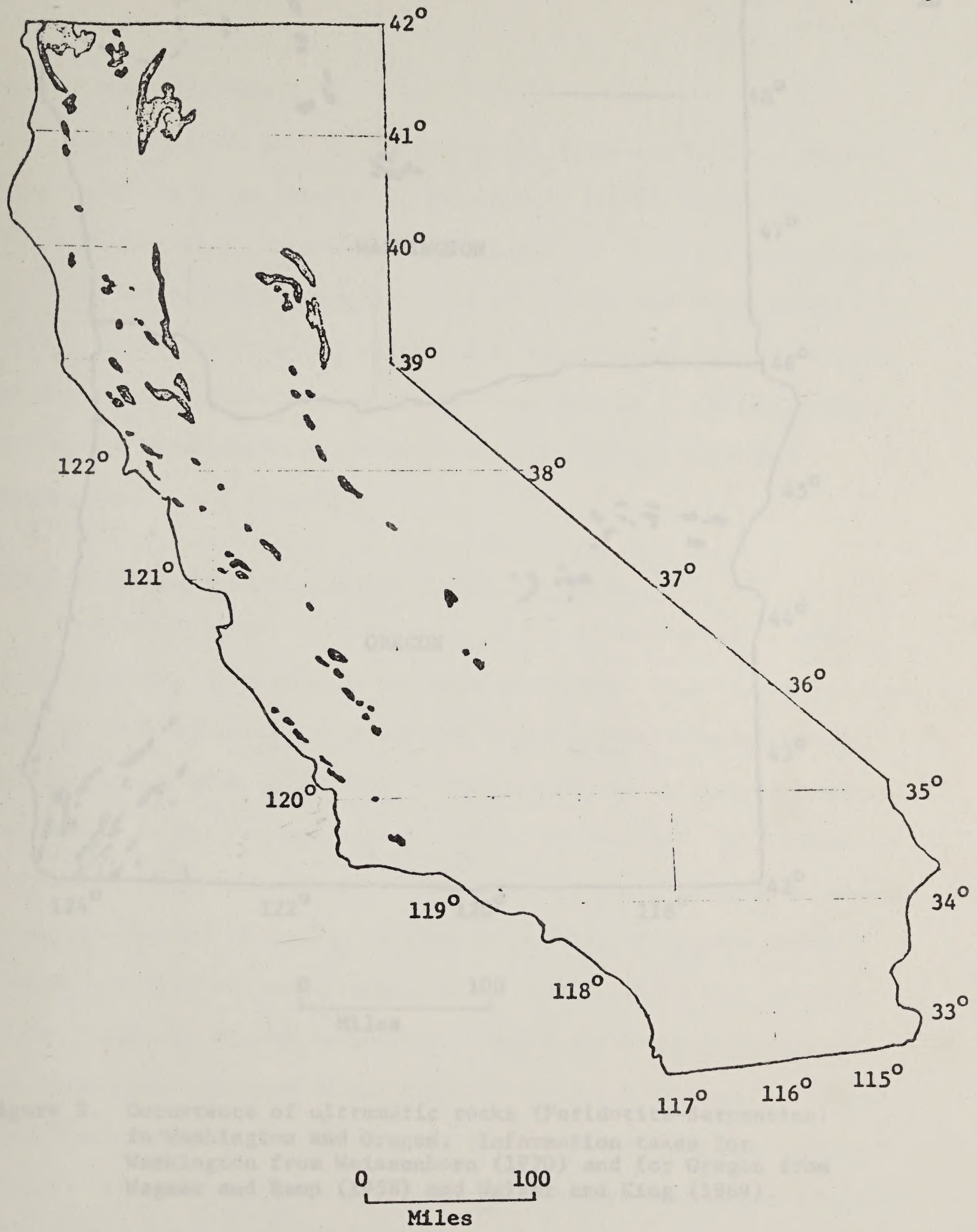
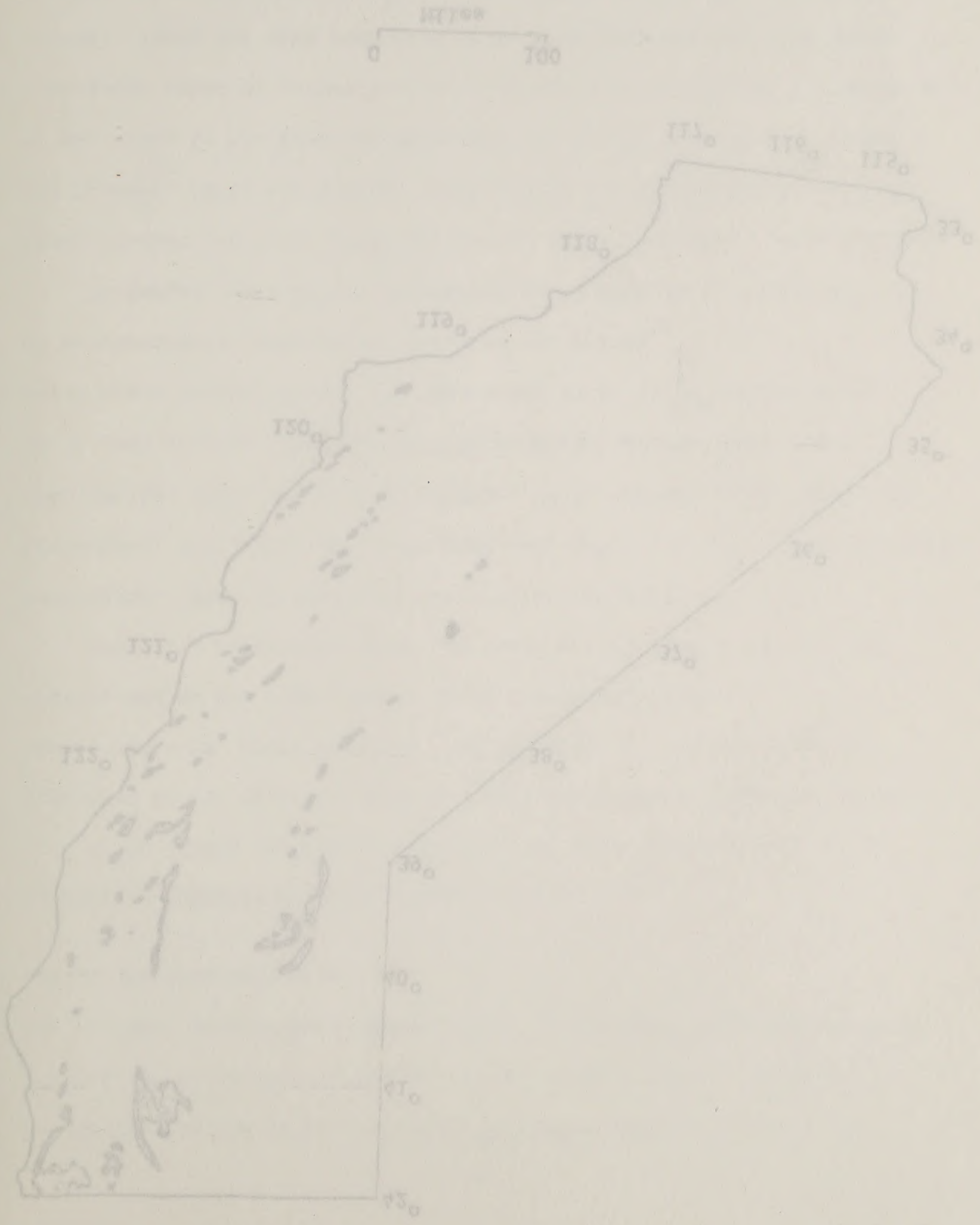


Figure 2. Occurrence of ultramafic rocks (Peridotite-Serpentine) in California. Information taken from U.S.G.S. and California Division of Mines (1966).



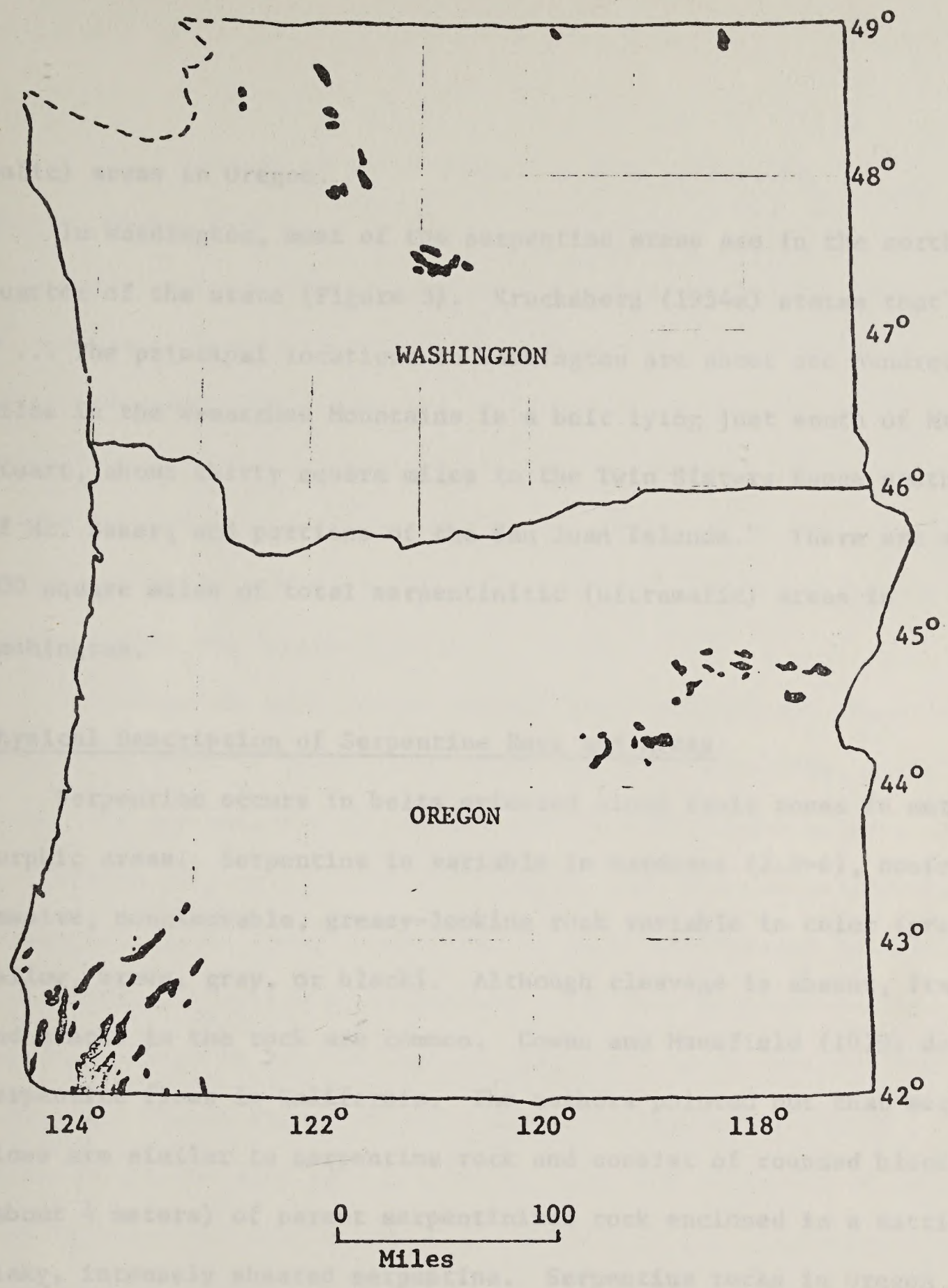


Figure 3. Occurrence of ultramafic rocks (Peridotite-Serpentine) in Washington and Oregon. Information taken for Washington from Weissenborn (1970) and for Oregon from Wagner and Ramp (1958) and Walker and King (1969).

mafic) areas in Oregon.

In Washington, most of the serpentine areas are in the northwest quarter of the state (Figure 3). Kruckeberg (1954a) states that " ... The principal locations in Washington are about one hundred square miles in the Wenatchee Mountains in a belt lying just south of Mt. Stuart, about thirty square miles in the Twin Sisters Range southwest of Mt. Baker, and portions of the San Juan Islands." There are about 200 square miles of total serpentinitic (ultramafic) areas in Washington.

Physical Description of Serpentine Rock and Areas

Serpentine occurs in belts oriented along fault zones in metamorphic areas. Serpentine is variable in hardness (2.5-6), nonfoliated, massive, noncleavable, greasy-looking rock variable in color (green, yellow, brown, gray, or black). Although cleavage is absent, fractures and cracks in the rock are common. Cowan and Mansfield (1970) described serpentine flows in California. The authors pointed out that serpentine flows are similar to serpentine rock and consist of rounded blocks (about 4 meters) of parent serpentinized rock enclosed in a matrix of flaky, intensely sheared serpentine. Serpentine rocks in Oregon and California generally are relatively hard (around 4 hardness) with some rock zones fairly soft but with hard centers (especially northeast of Ukiah). The most important physical characteristics of serpentine areas are outcrops of noncontiguous serpentine bodies (small in extent) (Figures 2 and 3), sharp boundaries with other rocks, and characteristic vegetation in comparison to nonserpentine areas.

APPARENT DEMONSTRATION OF PERPENDICULAR LOCK AND PLANE

NATURE OF SOILS DEVELOPED FROM SERPENTINE

General Characteristics

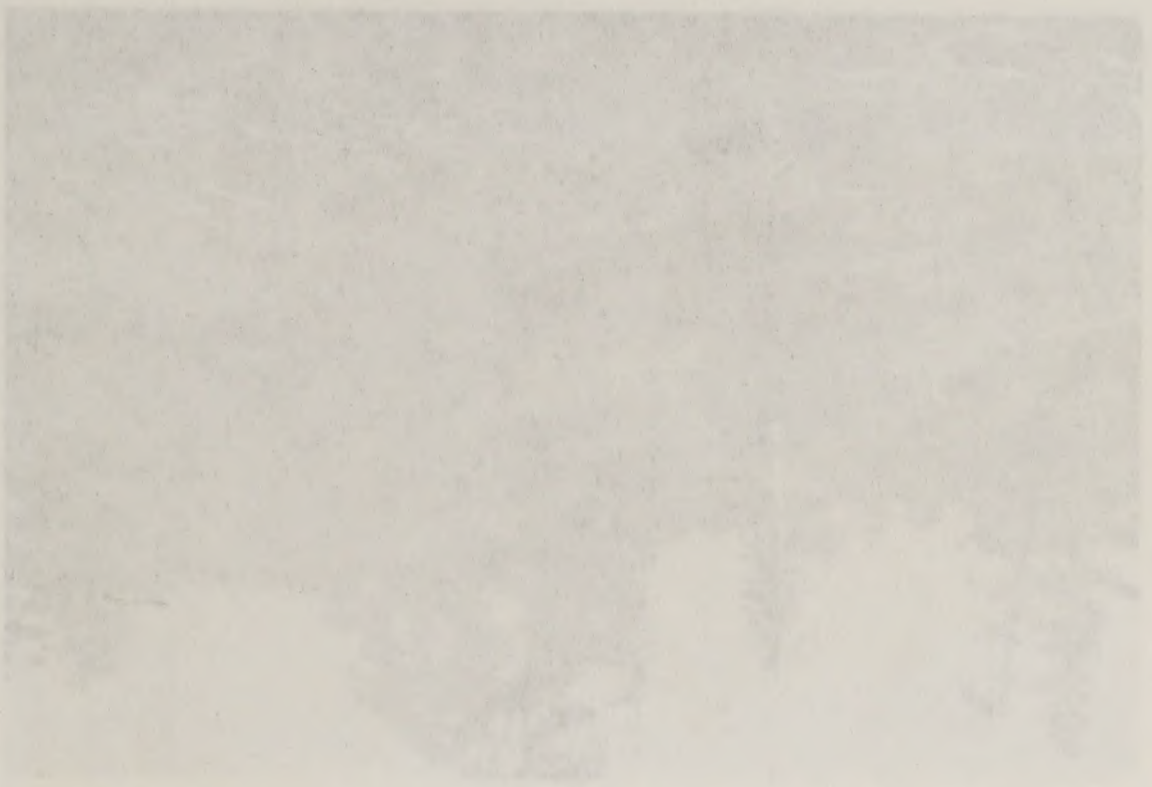
Soils derived from serpentine are generally shallow and stony in temperate climates but vary in thickness of solum depending upon the physiographic position, age of land surface, and climate. Generally, soils in swales and depressions are deep as compared to soils on upland rock exposures (Coombe and Frost, 1956a and 1956b). Serpentine derived soils formed under lateritic weathering are deep (Birrell and Wright, 1945; and Frasche, 1941).

Following are some of the general observations made regarding serpentine areas in Oregon and California. (1) Generally, soils on ridge tops and mountain slopes are shallow with deeper pockets in the depressions (Figure 4). (2) Deeper soils are found on relatively flat serpentine areas, lower slopes, and on areas with parent materials of mixed origin underlain by serpentine. (3) Open stunted woodland vegetation rich in endemic species (Figures 5 to 7) contrast with relatively closed stands on soils developed from other parent materials in the same area (Figure 6). (4) Few instances of soil or rock failures and mass movement are evident in the larger areas of serpentine and shallow soils but are commonly associated with narrow belts of serpentine oriented along fault zones with a thicker regolith or soil mantle. (5) Erosion has been active in the areas (especially on sparsely vegetated slopes). A large percentage of the areas have stone pavements left behind after removal of finer soil materials (Figure 7). (6) Serpentine ridge tops and mountain slopes have either scarce herbaceous vegetation or none at all where fire history and brush competition have been severe, but grass cover is fair under

General Characteristics

Fig. 4 . Typical soil profile developed from serpentine parent material showing shallowness and variability in thickness of solum and abrupt contact with bedrock. (Picture taken near O'Brien, Oregon.)

Fig. 5 . Typical vegetation on serpentine soils of Oregon (near O'Brien). Open forest of Jeffrey pine with manzanita, ceanothus, and fescue as ground cover on easterly aspect near ridge crest.



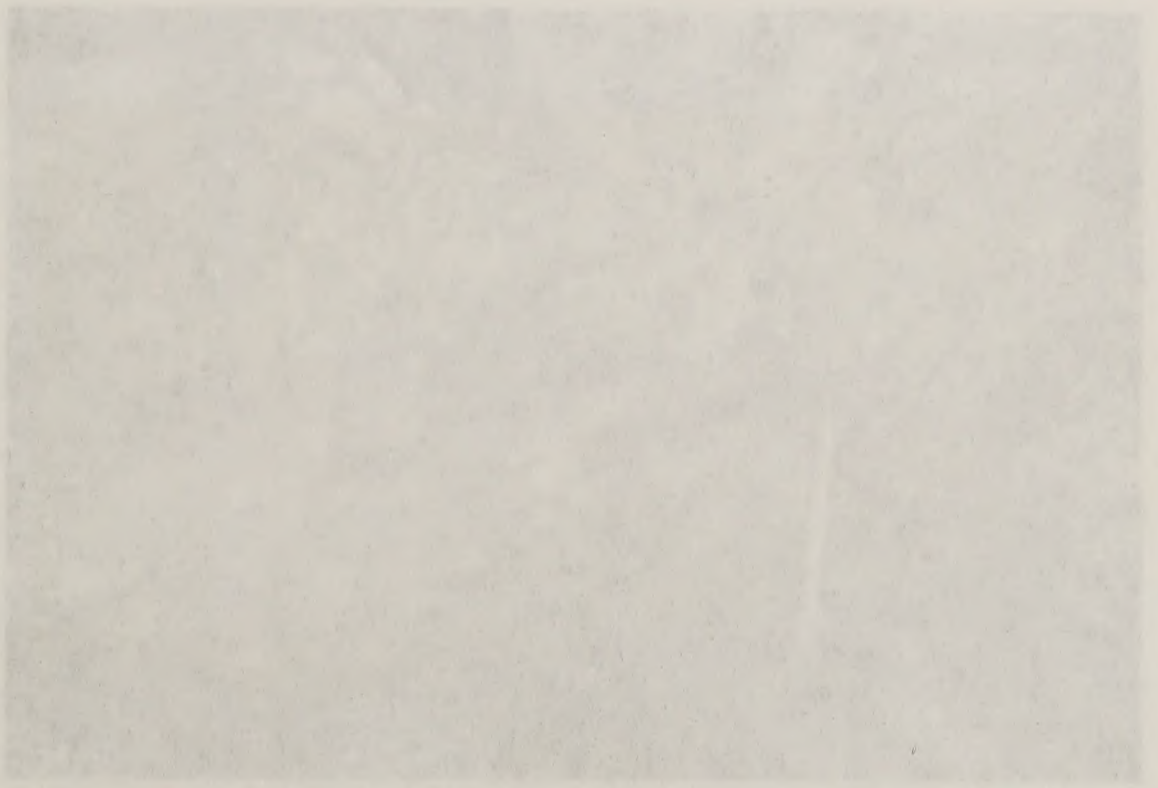
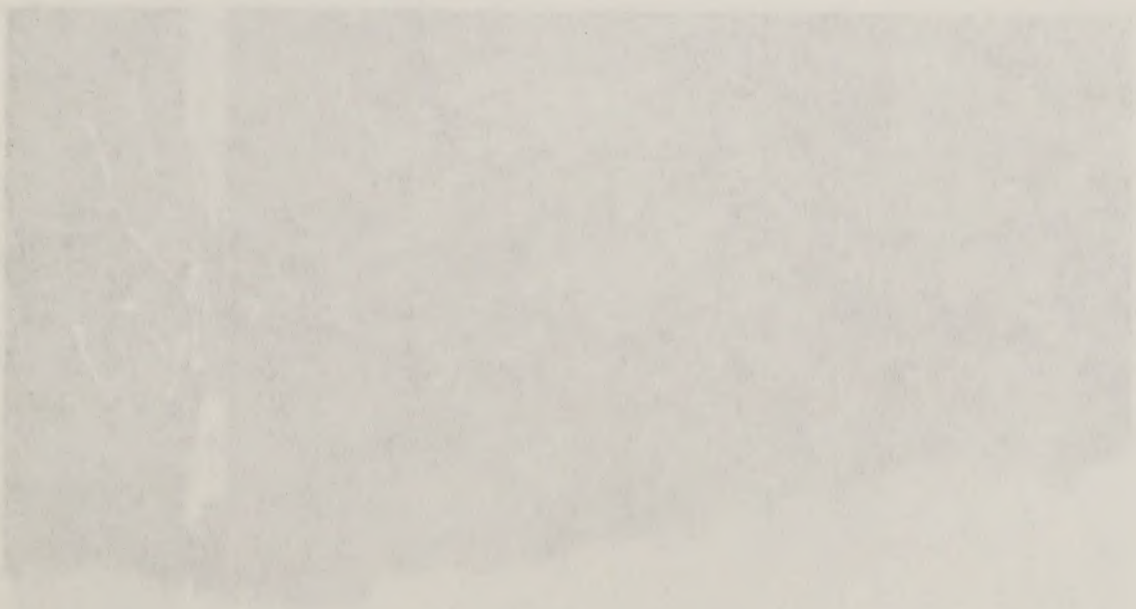


Fig. 6. Scrubby open forest of Jeffrey pine with manzanita, ceanothus, and fescue ground cover on serpentine soils (left) in contrast with closed canopy of Douglas-fir, sugar pine, and incense cedar on soils of mixed metamorphic parent material (right). (Picture taken of north-facing slope near O'Brien, Oregon.)

Fig. 7. Typical vegetation and stone pavement on serpentine soils near Ukiah, California (Red Mountain). Dense thickets of manzanita and cypress and scattered knobcone pine. Herbaceous vegetation is very scarce. Further east near Dollar Mountain, scrub oak and scattered digger pine are prominent.



open stands of pine with less shrub understory (Figure 5). (7) Shallow, stony soils with a dense cover of shrubs or scattered open stands of pine species predominate in serpentine areas over a wide range of annual precipitation (≈25 to 100 inches) indicating the strong influence of serpentine in modifying effects of climatic gradients.

Weathering of Serpentine Soils

The nature of the soil developed is dependent among other factors upon the chemical composition of the parent material. The comparison of chemical composition of parent material with that of soils developed from it helps to explain the weathering sequence of a soil. The chemical composition of some of the serpentine rocks and soils (Table 2) found under different weathering environments indicates that serpentine soils are low in Si and Mg, and high in Al, Fe, Cr, Ni, and Co in contrast with serpentine rock. The extent of losses and gains depends, however, upon the degree of weathering. The lateritic soils of New Caledonia (Birrell and Wright, 1945) are intensely weathered in comparison with lateritic soils of Oregon (Hotz, 1964) and Brown Forest soils of Japan (Kanno et al., 1965), consequently are lower in Si and Mg. It can also be noted that the ratio of Ca to Mg increases with increase in weathering. Butler (1953) and Veniale and Van der Marel (1963) also showed that relative increases in sesquioxides and decreases in Si and Mg occur as the weathering proceeds from rock to soil.

Wildman (1967) in generalizing the sequence of secondary mineral formation from serpentine parent materials states, " ... In the soils formed under climates of low weathering intensity, secondary minerals

Weathering of Carbonaceous Soils

Table 2. Chemical composition of serpentinitic rocks and soils.

Reference	Birrell and Wright (1945)			Hotz, 1964		Kanno, Tokudome, Arimura, and Onikura, 1965		
Area	New Caledonia			Oregon, U.S.A.		Japan		
Sample Description (depth inches)	Lateritic Soil (5-15)	Lateritic Soil (15-55)	Rock (>213.6)	Lateritic Soil (98.4-129.6)	Lateritic Soil (12-33.6)	Brown Forest Soil (Akamatsu Soil) Rock	(35-50)	(0-12)
SiO_2	3.95	12.11	43.0	35.1	18.5	39.20	38.62	41.44
Al_2O_3	4.87*	9.53*	1.6	3.5	6.9	2.13	3.82	5.13
Fe_2O_3	71.9	58.30	1.4	38.6	52.2	4.16	14.62	10.60
FeO	--	--	6.7	0.12	0.68	3.4	--	--
MgO	0.06	0.42	43.1	4.7	1.7	37.22	29.99	26.47
CaO	0.05	0.27	1.4	0.72	0.05	0.40	0.58	0.99
Na_2O	--	--	0.02	0.04	0.07	0.20	0.18	0.37
K_2O	--	--	0.02	0.02	0.05	0.04	0.05	0.16
P_2O_5	--	Trace	0.01	0.04	0.06	0.03	0.02	0.03
TiO_2	--	--	0.03	0.04	0.12	0.30	0.53	0.55
MnO	--	--	0.14	0.46	0.25	0.11	0.16	0.10
Cr_2O_3	3.05	3.12	0.36	1.2	2.1	0.39	0.76	0.81
CoO	--	--	0.02	0.07	0.13	0.01	0.02	0.01
NiO	0.16	0.30	0.37	2.0	2.0	0.23	0.39	0.21

* $Al_2O_3 + TiO_2$

Table 2. Chemical composition of serpentinite rocks and soils.

Reference	Harrell and Wright (1945)		Mocka, 1954			Ranno, Tolentino, Arizmendi, and Ontiveros, 1965	
Area	New Caledonia Soil		Oregon, U.S.A.			Japan	
Sample Description	New Caledonia Lateritic Soil		Rock	Lateritic Soil:		Brown Forest Soil (Akaoka Soil)	
(depth inches)	(3-15)	(15-55)	(>213.6)	(96.4-129.6)	(12-33.6)	Rock	(15-30) (0-15)
SiO_2	3.05	13.11	43.0	35.1	16.5	29.20	38.02 41.44
Al_2O_3	4.37*	9.39*	1.6	3.5	6.9	2.13	3.02 5.23
Fe_2O_3	71.9	36.20	1.4	32.6	31.2	4.18	14.87 10.60
FeO	—	—	4.7	0.12	0.68	3.4	— —
MgO	0.09	0.42	41.1	4.7	4.7	31.22	29.59 26.47
CaO	0.05	0.17	1.4	0.15	0.05	0.50	0.38 0.39
Na_2O	—	—	0.02	0.04	0.07	0.20	0.18 0.37
K_2O	—	—	0.02	0.02	0.05	0.04	0.03 0.16
P_2O_5	—	Trace	0.01	0.04	0.06	0.03	0.02 0.03
TiO_2	—	—	0.03	0.04	0.10	0.30	0.33 0.53
H_2O	—	—	0.14	0.44	0.25	0.11	0.16 0.10
CO_2	3.05	3.12	0.30	1.2	2.1	0.39	0.24 0.84
Cr	—	—	0.02	0.02	0.11	0.01	0.02 0.01
Ni	0.16	0.30	0.37	2.0	1.0	0.23	0.39 0.23

* $Al_2O_3 + TiO_2$

are likely to be high in silica ... As weathering intensity increases, secondary silicates of lower silica and base content, chlorite or kaolinite, are formed. Finally, removal of silica and bases is so pronounced that lateritic soils developing on serpentinites are predominantly iron and aluminum oxides".

Nagatsuka (1967) deduced that the weathering sequence of antigorite in humid and subtropical environments is as follows: Antigorite → expansible 14 Å mineral → randomly interstratified chlorite-aluminum vermiculite → chlorite.

Smectites (montmorillonite group) have been reported in soils developed from serpentine (Malquori and Cecconi, 1956; USDA, 1963; Wildman et al., 1968b; and Kanno, Onikura, and Tokudome, 1965). Butler (1953) reported that the predominant clay mineral in soils developed from serpentine in England are chlorite and illite. He also reported the presence of small amounts of kaolinite, montmorillonoid and talc. Veniale and Van der Marel (1963) working on the serpentine soils of Italy reported the presence of swelling chlorite and lizardite. Kanno, Onikura, and Tokudome (1965) reported that the major components of the clay fraction are antigorite, interstratified chlorite-aluminum vermiculite, and beidellite.

Wildman (1967) worked on soils of several serpentine areas of California. He reported that nontronitic montmorillonite with small amounts of residual serpentine are the only minerals identified by X-ray diffraction.

X-ray diffraction patterns of four serpentine soil clay samples (Nickel Mountain, Oregon, Sample No. III-1; and Waldo Hill, Oregon, Sample Nos. VIII-1, VIII-2, and VIII-3) with and without iron

removal were obtained using the following standard treatments: Mg saturated and 54% R.H., ethylene glycol, and glycerol; K saturated and 105°C, 300°C, and 550°C. With and without iron removal, the peaks were similar but the quality of the pattern was slightly improved with iron removal. The Nickel Mountain sample contained smectite, kaolinite and nonexpanding 2:1 mineral (possibly talc). The Waldo Hill samples (VIII-1,2, and 3) contained smectite and serpentine minerals. The results on Waldo Hill samples are similar to those of Wildman (1967) for California samples and are probably typical for Oregon soils. The Nickel Mountain sample is from an area of deeper Cornutt soils derived from ultrabasic rock and material from an exposure of laterite upslope.

Classification and Morphology of Soils

Serpentine weathers to give different genetic soil types under different weathering environments. Serpentine has weathered to "Smolnitsy" (meaning resin) in Albania (Bogatyrev, 1958). Brown Ranker, Eutrophic Braunerde, Pseudogley and Anmoor are found in England (Coombe and Frost, 1956a and 1956b) under cool humid temperate climates; Brown Forest (Kanno et al., 1965) and Podzol (Sasaki, et al., 1968) under subtropical humid and temperate climates, respectively; and Laterites in New Caledonia (Birrell and Wright, 1945), Phillipines (Frasche, 1941), and Cuba (quoted by Frasche, 1941) under tropical humid climates. Laterite is reported on remanants of old landscapes in Oregon (Wagner and Ramp, 1958; and Hotz, 1964). The latter probably is relict of an earlier cycle of weathering not related to the present climate.

Soils developed from serpentine in the western region of the United States fall into three orders, Inceptisols, Mollisols and Alfisols (Table 3). All these orders are represented in California and Oregon. Most of the type locations of soil series from serpentine listed in Table 3 are in California. This is not surprising since the most extensive serpentine areas occur in California.

Typically, serpentine derived soils of California and Oregon are reddish brown in color, shallow, very stony or cobbly, fine textured, and well drained. For the most part, these soils are in relatively steep, actively eroding topography and they exhibit a low degree of horizon development. Series with lithic and paralithic contacts to serpentine bedrock are recognized but lithic soils appear most extensive. The lower horizons of soils over the softer bedrock have greenish lithochromic colors. Both ochric and mollic epipedons occur but ochric (light colored or high chroma) surface horizons appear most extensive. The Pearsoll series in Oregon and the Henneke series of California are extensive. Other series with loamy, rather than clayey subsoils are recognized in California but their extent is not known.

Soils in concave upland draws, on foot slopes and on alluvial fans are generally deeper, darker, very fine textured and less than well drained, with dusky greenish to olive colored subsoils. The Brockman and Peel series in Oregon are typical of serpentine derived soils in these positions.

General Fertility

It is pointed out in the previous sections that the chemical composition and kind and amount of clay minerals in serpentine soils

Table 3. Soils derived from serpentine in the western region of the United States.

Series	Family	Subgroup
Dubakella	clayey-skeletal, serpentinitic, mesic	Typic Xerochrepts (Hapludalfs)
Pearsoll	clayey, serpentinitic, mesic	Lithic Xerochrepts
Weitchpee	fine-loamy, serpentinitic, mesic	Dystric Xerochrepts
Brockman	fine, mixed, mesic	Ultic Argixerolls
Henneke	clayey-skeletal, serpentinitic, thermic	Lithic Argixerolls
Montara	loamy, serpentinitic, thermic	Lithic Haploxerolls
Turnbow	loamy-skeletal, serpentinitic, mesic	Entic Haploxerolls
Delpiedra	loamy, serpentinitic, thermic, shallow	Mollic Haploxeralfs
Ishi Pishi	fine, serpentinitic, mesic	Typic Haploxeralfs (Haploudalfs)
Peel	fine, serpentinitic, mesic	Vertic Haploxeralfs
Sebastian	loamy, mixed, mesic	Lithic Haploudalfs

varies a great deal depending upon the nature of weathering. Hence, a great variation in amount and kind of exchangeable cations and in exchange capacities is expected. Data in Table 4 show that such is the case. However, high base saturation, the predominance of Mg as exchangeable cation, and a low ratio of exchangeable calcium to magnesium seems to be the common features. The serpentine soils have low available P and K, and the pH values are between 6 and 7 (Table 5).

Table 4. Cation exchange properties of some serpentine soils[a/] (Oregon and California).

Sample No.	Depth (cm)	Extractable Cations K	Na	Ca	Mg (me/100 g)	Cation Exchange Capacity	Saturation with Ca %	Saturation with Mg %	Ca/Mg
I-1	0-10	0.19	0.05	2.38	15.46	20.78	11.5	74.4	0.15
I-2	30-55	0.11	0.10	1.36	20.12	24.60	5.5	81.8	0.07
II-1	0-10	0.06	0.05	1.02	6.58	10.39	9.8	63.3	0.16
III-1	30-40	0.14	0.10	1.36	24.38	34.69	3.9	70.3	0.06
IV-1	0-10	0.25	0.10	2.55	1.11	15.4	16.6	7.2	2.30
IV-2	10-45	0.11	0.05	1.09	1.25	8.0	13.6	15.6	0.87
V-1	0-12	0.14	0.10	1.87	21.28	30.28	6.2	70.3	0.09
VI-1	10-30	0.11	0.05	1.19	12.58	22.54	5.3	55.8	0.09
VII-1	0-12	0.06	0.10	1.02	2.19	13.92	7.3	15.7	0.47
VII-2	12-40	0.11	0.29	0.68	2.06	13.72	5.0	15.0	0.33
VIII-1	0-15	0.17	0.05	3.40	27.65	41.75	8.1	66.2	0.12
VIII-2	15-40	0.11	0.05	2.04	38.22	46.16	4.4	82.8	0.05
VIII-3	40+	0.08	0.05	1.70	45.66	59.0	2.9	77.4	0.04
IX-1	10-30	0.14	0.05	5.78	9.96	21.36	27.1	46.6	0.58
X-1	0-10	0.36	0.10	8.01	25.82	36.9	21.7	70.0	0.31
XI-1	0-10	0.38	0.57	3.64	28.95	34.1	10.7	84.9	0.13
W-30* Lake Co., Calif.		0.11	0.05	2.12	12.1	14.2	14.9	85.2	0.18
W-37* Lake Co., "		0.13	0.04	2.33	19.7	22.3	10.4	88.3	0.12
W-50* Marin Co., "		0.37	0.13	3.20	11.2	17.0	18.8	65.9	0.29

[a/] Analyses were done by Soil Testing Laboratory, Oregon State University. Extractable cations and CEC were determined by using neutral normal ammonium acetate.

* Data of Whittaker (1954).

Sample No.	Depth (cm)	Extractable Cations (me/100 g) K	Na	Ca	Mg	Cation Exchange Capacity	Saturation with Ca %	Saturation with Mg %	Ca/Mg
I-1	0-10	0.19	0.05	2.38	15.46	20.78	11.5	74.4	0.15
I-2	30-55	0.11	0.10	1.36	20.12	24.60	5.5	81.8	0.07
II-1	0-10	0.06	0.05	1.02	6.38	10.39	9.8	63.3	0.16
III-1	30-60	0.14	0.10	1.36	24.38	34.69	3.9	70.3	0.06
IV-1	0-10	0.25	0.10	2.35	1.11	15.4	16.6	7.2	2.30
IV-2	10-45	0.11	0.05	1.09	1.25	8.0	13.6	15.6	0.87
V-1	0-12	0.14	0.10	1.07	21.28	30.29	5.2	70.3	0.09
VI-1	10-30	0.11	0.05	1.18	12.59	22.84	5.1	55.8	0.09
VII-1	0-12	0.06	0.10	1.01	2.19	13.91	7.3	15.7	0.47
VII-2	12-40	0.11	0.05	1.06	2.06	13.12	5.0	15.0	0.33
VIII-1	0-15	0.17	0.05	3.40	27.05	41.25	8.1	66.2	0.12
VIII-2	15-40	0.11	0.05	2.04	28.22	46.18	4.4	82.8	0.05
VIII-3	40+	0.08	0.05	1.70	45.66	59.0	2.5	77.4	0.04
IX-1	10-30	0.14	0.05	5.78	9.96	21.36	27.1	46.6	0.58
X-1	0-10	0.36	0.10	8.01	15.82	36.0	21.7	70.0	0.51
XI-1	0-10	0.39	0.27	3.64	28.95	34.1	10.7	84.9	0.13
W-30*	Lake Co., Calif.	0.11	0.05	2.11	12.1	14.2	14.9	85.2	0.18
W-37*	Lake Co.,	"	0.11	0.04	2.35	10.7	23.3	10.4	84.3	0.12
W-30*	Yuba Co.,	"	0.37	0.11	3.30	11.2	17.0	18.8	65.9	0.29

1/ Analyses were done by Soil Testing Laboratory, Oregon State University. Extractable cations and CEC were determined by using neutral normal ammonium acetate.

* Data of Whittaker (1956).

Table 5. Available nutrient status of some serpentine soils[a/] (Oregon and California).

Sample No.	Depth	pH	Available P	Available K
	(cm)		(ppm)	(ppm)
I-1	0-10	6.3	7.9	76
I-2	30-55	6.3	5.9	43
II-1	0-10	6.5	5.9	22
III-1	30-40	6.2	4.9	54
IV-1	0-10	5.8	4.4	96
IV-2	10-45	5.9	3.3	43
V-1	0-12	6.6	5.9	54
VI-1	10-30	6.7	3.9	43
VII-1	0-12	6.4	5.9	22
VII-2	12-40	6.4	5.9	43
VIII-1	0-15	6.6	5.9	65
VIII-2	15-40	6.4	5.9	43
VIII-3	40+	6.5	4.9	33
IX-1	10-30	6.7	4.9	54
X-1	0-10	6.8	3.3	139
XI-1	0-10	7.0	3.3	149

[a/] Analyses were done by the Soil Testing Laboratory, Oregon State University. 1:2 soil water suspension was used for pH determination. Bray's dilute acid fluoride method (modified by using Vanadate yellow as coloring agent) was used for determination of available phosphorus. Extractable K values were used to calculate available K.

SERPENTINE SOIL AND VEGETATION RELATIONSHIPS

General Relationships

The poor growth of plants on serpentine, the sharp differences in vegetation of serpentine and nonserpentine soils, and narrow endemic flora of serpentine have attracted studies on the relation of serpentine soil to plant ecology. These include studies of the response of plant species to serpentine and nonserpentine soil (autecological), and of the peculiarities of serpentine vegetation (synecological) [Whittaker, 1954a]. There are few studies on the relation of serpentine soils to plant ecology in comparison to studies on the other aspects.

The plants occurring on serpentine soils can be divided on the basis of their extent (or affinity to serpentine soil) into the following three categories: (1) Serpentine characteristic plants (plants which are more or less restricted to serpentine soils), (2) Serpentine indifferent plants (plants which occur with same ease on serpentine and nonserpentine soils), and (3) Serpentine accidental plants (plants which mainly occur on nonserpentine) [Rune, 1953]. Knuckeberg (1954) indicated that plants which grow on serpentine soil and the plants that grow on serpentine and nonserpentine soils do so because their population is specially adapted to physical and chemical properties of the serpentine soils.

The plants which mainly occur on serpentine soils have been variously characterized as serpentine plants, serpentine characteristic plants, serpentinicolous, serpentinophytes, serpentine endemics or serpentinomorphoses (Rune, 1953). Pichi Shermolli (1948) divided serpentinicolous plants into two categories, "serpentinophytes"

GENETIC RELATIONSHIPS

(neoendemics, differentiated within the serpentine areas) and "serpentinicolous relics" (epibiotics, more or less restricted to serpentine habitats since they became extinct outside) depending upon their mode of origin. Stebbins (1942) defined an endemic plant as " ... One poor in biotypes and with its biotypes so specialized that they can grow and compete with other species in only a limited area." He proposed the following types of endemics: (1) "depletion" (the endemic status acquired by the species through loss of most of its biotypes which formerly allowed the species to exploit a greater variety of habitats) and (2) "insular" (originated from isolated individuals pre-adapted to a specific habitat situation). Pichi Shermolli's (1948) serpentinophytes category is equivalent to insular endemic of Stebbins (1942) and serpentinicolous relic to depletion endemic. Serpentine races which show morphological changes, hereditarily fixed as well as non-hereditarily modified, are called serpentinomorphoses.

Vegetation of Serpentine Areas in California, Oregon and Washington

Many workers have described the species composition of various serpentine areas. In general, the composition of vegetation flora on serpentine soils changes with climate but is more xeric and specialized than on adjacent nonserpentine soils. Franklin and Dyrness (1969) have summarized the vegetation of serpentine areas in California, Oregon and Washington. Whittaker (1960) and Waring (1969) described most xeric serpentine sites of Siskiyou Mountains (300-2000 meter elevations) as Jeffrey pine/grass[5/] woodlands.

5/ Scientific names of plants are given in Appendix II.

The present study indicates that typical serpentinic vegetation of the Siskiyou Mountains in Oregon and California consists of open forest of Jeffrey pine with manzanita, Ceanothus and fescue as ground cover (Figures 5 and 6). Generally, the brush is rather scattered with grass covered openings. Chaparral is the typical vegetation of serpentinic soils in the California Coast Ranges north of San Francisco. Near Ukiah on Red Mountain, the vegetation consists of dense thickets of manzanita and cypress with scattered knobcone pine (Figure 7). Further east near Jim Dollar Mountain, there is a dense brush cover of scrub oak, cypress and manzanita with scattered digger pine (Figure 7). Chamise dominates the adjacent nonserpentine areas of chaparral. Almost no grass exists in these brush lands which have a history of frequent wild fires. Franklin and Dyrness (1969) mentions sparse growth of the following grasses in the open woodlands of Siskiyou Mountains: lemmon needle grass, big squirreltail, geyer oniongrass, sheep fescue, and blue wildrye. Whittaker (1960) noted several conifers - Jeffrey pine, sugar pine, knobcone pine, Douglas-fir, and incense cedar - on sites intermediate in elevation and moisture regime. Whittaker (1960) also pointed out that Jeffrey pine, Western white pine, knobcone pine, canyon live oak, narrowleaved buckbrush, and pine-mat manzanita serve as serpentine indicator plants.

Franklin and Dyrness (1969) noted that serpentine areas at lower elevations in Washington have Douglas-fir, lodgepole pine, and Western white pine as typical vegetation whereas at higher elevations, it is whitebark pine and subalpine fir. The authors mentioned that pine-mat manzanita and common juniper are typical shrubs of the areas. Kruckeberg

(1964) considers Mt. Stuart bluegrass, podfern, snow douglasia, blunt-leaved sandwort, oarleaf buckwheat, and alpine springbeauty as serpentine indicator species in the Wenatchee Mountains area.

CAUSES OF INFERTILITY OF SERPENTINE SOILS

Various workers have advanced hypotheses to explain the peculiarities of vegetation on serpentine. Complete information on the simultaneous effects of the various causes hypothesized for poor growth is lacking. In general, most workers recognize the influence of various limiting factors (physical characteristics of soils; high pH; low levels of available molybdenum; absence of soil micro-organisms; low levels of N, P, and K; high amounts of available micronutrients; and low percentage saturation with Ca), but they differ on the dominant cause of infertility of these soils. The variation in dominant cause or causes is expected since these workers studied serpentine soils developed under various weathering conditions in different geographic locations. For an example, the dominant cause of infertility of highly weathered, low pH lateritic soils probably is the toxic amounts of available micronutrients whereas, for weakly weathered, shallow stony soil it probably is the physical characteristics. There may, of course, be more than one limiting factor acting simultaneously in these soils. A discussion of each of the major hypotheses follows.

Physical Properties

The coarse fragment content and shallowness of serpentinic soils have a great influence on vegetative cover because of low water-holding capacity and restricted soil depth for penetration of roots. Harshberger (1903) reports that soils developed from serpentine in Pennsylvania are shallow. The flora is relatively barren in appearance, and that the types of flora differ sharply from the

surrounding relatively deep, nonserpentine soils. Similar conditions predominate in serpentine areas observed in Oregon and California. This indicates that physical conditions (especially shallowness) of the serpentine soils play an important part in favoring characteristic serpentine flora. Waring (1969) reported that most serpentine soils are droughty. Whittaker (1954b and 1960) generalized that plants growing in the same general location on serpentine and nonserpentine soils show tendency of displacement towards more xeric sites on serpentine soils in contrast with plants growing on nonserpentine soils (from gabbro and dioritic parent materials).

The predominant exchangeable cation of serpentine soils is Mg. Most of the deeper and many shallow serpentine soils are high in clay content. Usov (1937) and Bogatyrev (1958) reported that high magnesium imparts some saline properties to these soils. High clay contents may also affect physical behavior of the soils by causing low permeability. Robinson et al. (1935) did not find any physical properties which would render serpentine soils unfavorable for plant growth. The authors did find clay contents in some soils high enough to impede drainage and possibly restrict root growth somewhat.

The shallowness, droughtiness, and other adverse (for plant growth) physical properties probably are partly the cause of poor plant growth on many serpentine soils. This cannot, however, be the general cause of infertility since there are some deep serpentine soils with good physical properties which are also infertile.

High pH Values

Gordon and Lipman (1926) reported high pH values for some California serpentine soils. They suggested that the alkaline reaction

of serpentine soils contributes to their infertility. Burgy (1970) also reported high pH values (>8) as well as pH values between 6 and 7 for soils over serpentine rock. Careful examination of Burgy's report indicated that soils with high pH values are developed from mixed parent materials of serpentine and diabase. The literature (Whittaker, 1954; Coombe and Frost, 1956a and 1956b; and Burgy, 1970) and data of this study indicate that the pH of most serpentine soils is between 6 and 7. There are also some serpentine derived soils developed under lateritic weathering which have pH values around 5.5 (Hunter and Verganano, 1952; Birrell and Wright, 1945; and Crooke 1956).

It is clear from the above that there may be only few serpentinic soils with high pH values and hence alkalinity is not a general cause of infertility of serpentine soils.

Low Levels of Available Molybdenum

Johnson et al. (1952) grew 30 crop species on fertilized (N, P, and K) California serpentine soils. The grasses (barley, oats, and wheat) and legumes (cow peas and beans) showed no molybdenum deficiency whereas other species showed molybdenum deficiency symptoms which were corrected on application of molybdenum. Walker (1954) also observed deficiency symptoms of molybdenum on tomato and Romaine lettuce, which were only corrected by the application of molybdenum. Yatazawa and Tanaka (1965) used Aspergillus niger to test the availability of Mo in some Japanese serpentine soils. The results showed that the serpentine soils are low (or almost deficient) in available molybdenum.

At present, there is not enough evidence to indicate that low levels of available molybdenum is a characteristic feature of all

Two Levels of Multiple Inheritance

serpentine soils.

Absence of Soil Microorganisms

Lipman (1926) studied microbial populations of serpentine soils from California. He reported that there is an absence of nitrifying bacteria and that the microorganism population consists mainly of nonchromogenic bacterial forms, very few fungi, actinomyces, and azotobactor (only in one of the three soils). The author indicates that scarcity or absence of microbial populations may be a cause of poor nutritional status of serpentine soils. Tadros (1957) grew Emmenanthe Penduliflora (nonserpentine herb) and Emmenanthe rosea (serpentine herb) on serpentine and nonserpentine soils and in sand cultures. E. rosea showed more tolerance to high Mg and to deficiency of Ca, K, and P. The rate of survival of E. rosea was low when it was grown on nonsterilized garden soil as compared to one type of serpentine soil (Henneke series). E. rosea was more tolerant than E. Penduliflora when the above soils were sterilized. The best survival rate and growth response of E. rosea was obtained on sterilized serpentine (Montana series) and garden soil. This indicates the absence of soil microorganisms in serpentine soils, which hinder the growth of serpentine tolerant species on more fertile soils.

There is not enough evidence to indicate that the absence of soil microorganisms is characteristic of all serpentine soils or that this is a general cause of the infertility of serpentine soils.

Low Levels of Available N, P, and K

In general, serpentine soils are deficient in available major nutrients (Lipman, 1926; Gordon and Lipman, 1926; Vlamis and Jenny,

1948; Vlamis, 1949; Birrell and Wright, 1945; Johnson et al., 1952; and this study). The application of major nutrients (especially N, P, and K) results in increased production (Gordon and Lipman, 1926; Vlamis and Jenny, 1948; and Vlamis, 1949). Ishimoto (1958) reported stunted and endemic flora on serpentine soils which were adequate in available N, P, and K.

Although most serpentine soils are deficient in available major nutrients and they respond to their application, applications of major nutrients alone have failed to correct their infertility in most cases.

Excessive Amounts of Available Micronutrients

The increase in weathering intensity of serpentine rock results in increased total contents of micronutrients (Ti, Mn, Co, Cr, and Ni) in the serpentine soils (Birrell and Wright, 1945; Hotz, 1964; and Kanno et al., 1965). The availability of a micronutrient, among other factors, is most dependent on the total content of a micronutrient in the soil. Consequently (if other factors are favorable), higher amounts of certain available micronutrients is expected from serpentine soils in comparison to soils weathered from other parent materials. Many research workers have reported higher amounts of available nickel (Birrell and Wright, 1945; Crooke, 1956; Hunter and Vergnano, 1952; Minguzzi and Vergnano, 1953; and Spence, 1957), chromium (Birrell and Wright, 1945; Minguzzi and Vergnano, 1953; and Spence, 1957), cobalt (Minguzzi and Vergnano, 1953), and copper and zinc (Yatazawa, and Tanaka, 1965) in soils developed from serpentine. Hunter and Vergnano (1952) reported 22-61 ppm exchangeable Ni in serpentine soils in comparison to 0.2 ppm exchangeable Ni content of normal soils.

Excessive amounts of available microcontaminants

Most of these research workers point out that the availability of micronutrients (especially Ni and Cr) in toxic amounts may be the major cause of the infertility of serpentine soils. Birrell and Wright (1945) reported 86.3 ppm of Ni and 4.5 ppm of Cr in the dry leaf tissue of Pancheria glabrosa growing on an acid tropical serpentine soil. Hunter and Vergnano (1952) reported 17-134 ppm of Ni in oat leaves whereas the Ni content of normal oat leaves is 3 ppm. Spence (1957) reported 90-118 ppm of Ni in dry matter of Agrostis stonifera. Vergnano (1953) working with 2.5 ppm of Ni solution observed Ni toxicity symptoms on crop plants similar to those observed on crop plants grown on serpentine soils. Hence, research indicates that serpentine flora and soils have higher concentrations of micronutrients in comparison to normal soils and their flora. Rune (1953) pointed out that the total effect of these elements on plant growth would depend upon pH, low nutrient contents, absence of Ca, high magnesium content, presence of reduced iron, and mechanical composition of soils. One of the important factors which increase the available contents of micronutrients (Ni) of soils and ultimately total contents of serpentine plants is low pH (Hunter and Vergnano, 1952 and Crooke, 1956).

Toxic levels of micronutrients (especially Ni and Cr) are important factors in making low pH serpentine soils infertile. All serpentine soils do not have low pH's and hence this cannot be the general cause of infertility of serpentine soils.

Low Percentage Saturation With Calcium

The total Mg content of serpentine rocks is in the order of 40 percent. Calcium is absent from pure serpentine minerals. The percentage of Ca in serpentine rocks, however, varies depending upon

the contents of calcium bearing minerals present. Usually, calcium content of rocks is about one percent. This indicates that the calcium to magnesium ratio in rocks is very low. Soils derived from serpentine have lower percentages of magnesium than serpentine rocks. Magnesium tends to leach with increasing weathering intensity (Frasche, 1941; Birrell and Wright, 1945; Butler, 1953; Hoyos De Castro, 1960; Hotz, 1964; and Kanno et al., 1965). This study and literature (Walker, 1948; Ishimoto, 1958; USDA, 1963; and Kanno et al., 1965) indicates that magnesium is the predominant exchangeable cation, even after soils have gone through varying degrees of weathering. The exchangeable calcium to exchangeable magnesium ratio of serpentine soils is much less than one.

Loew and May (1901) and Novak (1928) indicated that the low calcium to magnesium ratio is an important factor in determining infertility of serpentine soils. Recent research indicates that high magnesium makes calcium less available (already in very small amounts in these soils) which, in turn, affects plant growth. Most studies have proved experimentally that the low availability (or low percent saturation of CEC with Ca) of calcium is the cause of infertility of serpentine soils rather than low calcium to magnesium ratio (Moser, 1933; Vlamis and Jenny, 1948; Vlamis, 1949; Martin et al., 1953; Walker, 1954; and Walker et al., 1955).

The degree of saturation of soil with calcium plays a very important role in controlling the yields of various species. The yields of various species were small with low calcium saturation but optimum yields were obtained with calcium saturation of about twenty percent (Moser, 1933; Vlamis, 1949; Martin et al., 1953; and Walker et al., 1955). Walker et al. (1955) showed that yields of crop plants were very

much affected by exchangeable calcium levels. There was very little growth at calcium levels of less than 10%. The authors also showed that yields of native plants (serpentine endemics) were not affected by calcium levels (6-82%). The native plants absorbed more calcium and less magnesium at lower levels of exchangeable calcium (3-15%) than crop plants. This study indicates that serpentine species are able to absorb more calcium (from calcium deficient soil) than crop plants.

The preceeding indicates that low levels of exchangeable Ca may be the general cause of infertility (or the most limiting factor of plant growth) of serpentine soils, since most serpentine soils are deficient in calcium.

SUMMARY

Serpentine is highly altered ultramafic rock. It generally occurs in small rock exposures in various parts of the world. The most extensive serpentine areas in the United States are in Caliornia, Oregon, and Washington. There are about 1100, 450, and 200 square miles of ultramafic (serpentine-peridotite) areas in California, Oregon, and Washington, respectively. In general, serpentine areas have poor stunted flora rich in endemics.

Serpentine weathers to give different weathering products and different genetic soil types under various weathering environments. Serpentine derived soils are generally low in total Si and Mg and high in Al, Fe, and microelements (such as Ti, Co, Ni, and Cr) in comparison with serpentine rocks. The total absolute differences, of course, depends upon the intensity and kind of weathering. Serpentine weathers to smectite type clay minerals under low weathering intensity, to chlorite or kaolinite type clays under medium intensity, and to elemental oxides (especially Al_2O_3 and Fe_2O_3) under high weathering intensity. The above indicates that the properties of soils derived from serpentine depend upon the kind and intensity of weathering. However, serpentine soils, in general, are high in base saturation and exchangeable magnesium and low in percent of exchangeable calcium, have low calcium to magnesium ratios and are low in available macronutrients (especially N, P, and K). Most serpentine soils have adverse physical characteristics for plant growth and some have high amounts of available micronutrients (especially Ni and Cr). Rock and soil failures are commonly observed in serpentine areas. Rock failures are probably due to the highly fractured nature and other physical characteristics of serpentine rocks. Soil failures

are probably due to the high contents of swelling clay, high contents of magnesium on the exchange complex, steep slopes, and poor open flora.

On-site observations of serpentine areas in Oregon and California were made. In general, the soils are shallow (especially on ridge tops), very stony or cobbly, reddish brown in color, fine textured and well drained. A dense cover of shrubs or scattered open stands (rich in endemics) of pine species are typical of serpentine areas of California and Oregon. Erosion is active in the areas (especially on sparsely vegetated steep slopes). Serpentine soils are classed in the Inceptisol, Mollisol, and Alfisol orders. The Pearsoll series in Oregon and Henneke series of California are extensive.

Typical serpentine rock and soil samples from Oregon and California were analyzed. The DTA thermogram and X-ray diffraction pattern of powdered rock sample show that the rock sample consists exclusively of serpentine group minerals. X-ray diffraction of clay samples of soil most probably derived from the above rock shows that smectite and serpentine group minerals are the only minerals present in the soil. Another sample (from a different locality) contained smectite, kaolinite, and a 2:1 nonexpanding mineral (possibly talc). Serpentine soil samples analyzed for nutrient contents show that the soils are low in available macronutrients (P and K), percent exchangeable calcium, have low calcium to magnesium ratios and high base saturation and exchangeable magnesium. These characteristics are similar to those reported for serpentine soils elsewhere.

The vegetation on serpentine soils is generally poor in growth and consists either of open stunted tree stands with scarce understory or dense chaparral. Some species are restricted to serpentine, others

grow on both serpentine and nonserpentine, and still others mainly grow on nonserpentine. The species which grow well or survive on serpentine must be adapted to the physical and chemical properties of the serpentine soils.

The influence of adverse physical and chemical properties on infertility of serpentine soils is discussed. These properties may include restricted rooting depth, stoniness, low levels of available molybdenum, absence of soil micro-organisms, low levels of available macronutrients (N, P, and K), excessive amounts of available micronutrients, high pH values, and low percentage saturation with calcium relative to magnesium. Any one or more than one of the above may be the dominant cause or causes of infertility for different serpentine soils.

SERPENTINE SOILS RESEARCH NEEDS AND MANAGEMENT

Areas of serpentine soils in southwestern Oregon and northern California are predominantly in public ownership under control of the U. S. Forest Service or Bureau of Land Management. There are about 120 square miles of serpentine-peridotite (ultramafic) in Oregon and 230 square miles in California under the Bureau of Land Management.

Observations during this study and comments by the local resource managers indicate a low level of use and management of these lands. Generally, serpentine areas within forest zones are classed as non-commercial and are not included in the timber base of the local management units.

The low stand density of Jeffrey pine woodlands suggests there are problems with regeneration. However, seedlings seemed to be plentiful in many areas, though rather irregular in distribution. Possibly, the thin stands are all that can be supported by the shallow, stony soils. Areas marginal to bodies of serpentine with a regolith of materials derived from mixed serpentine-nonserpentine rock types were observed to sometimes have a somewhat better stand with more tree species present.

Grazing by livestock is not a common practice although some range use apparently is made of serpentine soils in interior areas of northern California. Chaparral areas produce little forage and are not generally grazed by livestock. An experimental burn reseeding observed near Jim Dollar Mountain in Lake County appeared to have a fair cover of introduced grasses, although the cover was somewhat spotty. No grazing allotment had been applied for in the area. Shrub areas dominated by

cypress are resistant to brush eradication by fire, chemicals, or mechanical means.

Wildlife habitat and watershed values are the major uses of most serpentine soil areas at present. The nutritional limitations for deer of browse and forage from serpentine soils are not known. Burgy, 1970 reports data indicating an increase in water yield of over five acre inches can be expected by changing from brush to grass cover in the chaparral areas of central California. Research on establishment of grass on serpentine soils after brush clearing is being initiated by the Hopland Field Station of the University of California in cooperation with the Bureau of Land Management[6/]. This study will give information on adaptability and nutrient requirements of grass species on serpentine soils in the region.

Soils within areas of serpentine that have some potential for timber production are generally in higher precipitation zones and have deeper than average profiles. Often these deeper soils appear to have formed from mixed materials rather than pure serpentine. Investigation is needed to evaluate the potential productivity, regeneration problems, nature and degree of nutrient limitations, occurrence in the landscape, extent, and morphological distinction of these soils from mixed materials.

Information is also needed regarding the potential erosion and instability problems on these soils when managed for timber production. Other investigations that would be useful for management of serpentine soil areas are:

6/ Personal communication with Dr. Milton Jones, Hopland Field Station, Ukiah, California.

\3\ Personal communication with Dr. Milton Jones, Hoover Field Station, Alameda, California.

Study of the nutritional quality of natural or introduced forage and browse for deer and livestock.

Study of livestock grazing potential in the open-stand Jeffrey pine woodlands.

Study of the economics and management problems of range use for the (a) woodland areas, and (b) renovated chaparral areas.

Study of field criteria for identification of critical areas of landscape instability.

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Appendix I. Serpentine soil sample locations.

Sample No.	Area	Location	Horizon	Depth (cm)	Moist Color	Dry Color	Texture
I-1	Cow Creek (South), Oregon	SW¼, SE¼, Sec. 25, T30S., R.7W.	A	0-10	Dark brown (7.5YR 3/2)	Brown (7.5YR 5/4)	Clay loam
I-2	"	"	B	30-55	Dark reddish brown (5YR 3/2)	Brown (7.5YR 4/2)	Gravelly clay
II-1	Cow Creek (North), Oregon	Sec. 24, T.30S., R.7W.	A	0-10	Dark reddish brown (5YR 3/2)	Reddish brown (5YR 6/6)	Clay loam
III-1	Nickel Mountain, Oregon	SW¼, Sec. 17, T.30S., R.6W.	B	30-40	Dark reddish brown (2.5YR 3/4)	Reddish brown (2.5YR 4/4)	Clay
IV-1	Serpentine Spring, Oregon	NE¼, SW¼, Sec. 31, T.34S., R.8W.	A	0-10	Dark reddish brown (5YR 3/4)	Brown (7.5YR 4/4)	Clay loam
IV-2	"	"	B	10-45	Dark brown (7.5YR 4/4)	Strong brown (7.5YR 5/7)	Clay loam
V-1	Onion Camp, Oregon	Sec. 29, T.38S., R.9W.	A	0-12	Dark reddish brown (5YR 3/3)	Reddish brown (5YR 4/4)	Gravelly clay loam
VI-1	Bain Station, Oregon	SW¼, NE¼, Sec. 13, T.41S., R.10W.	B	10-30	Dark brown (7.5Y 3/2)	Brown (7.5YR 4/4)	Gravelly clay loam
VII-1	Oregon Mountain, Oregon	NE¼, NE¼, Sec. 17, T.41S., R.9W.	A	0-12	Dark reddish brown (5RY 3/3)	Reddish brown (5YR 4/4)	Gravelly clay loam
VII-2	"	"	B	12-40	Reddish brown (5YR 4/4)	Yellowish red (5YR 4/6)	Gravelly clay loam
VIII-1	Waldo Hill, Oregon	NW¼, SW¼, Sec. 33, T.40S., R.8W.	A	0-15	Dark reddish brown (2.5YR 2/4)	Dark reddish brown (2.5YR 3/4)	Gravelly clay
VIII-2	"	"	B	15-40	Dark reddish brown (2.5YR 2/4)	Dark reddish brown (2.5YR 3/4)	Gravelly clay

Appendix I. Serpentine soil sample locations.

Sample No.	Area	Location	Horizon	Depth (cm)	Moist Color	Dry Color	Texture
I-1	Cow Creek (South), Oregon	SW¼, SEL, Sec. 25, T.30S., R.7W.	A	0-10	Dark brown (7.5YR 3/2)	Brown (7.5YR 5/4)	Clay loam
I-2	"	"	B	30-55	Dark reddish brown (5YR 3/2)	Brown (7.5YR 4/2)	Gravelly clay
II-1	Cow Creek (North), Oregon	Sec. 24, T.30S., R.7W.	A	0-10	Dark reddish brown (5YR 3/2)	Reddish brown (5YR 5/3)	Clay loam
III-1	Nickel Mountain, Oregon	SW¼, Sec. 17, T.34S., R.6W.	B	30-40	Dark reddish brown (2.5YR 3/4)	Reddish brown (2.5YR 6/4)	Clay
IV-1	Serpentine Spring, Oregon	NE¼, SW¼, Sec. 31, T.34S., R.5W.	A	0-10	Dark reddish brown (2YR 3/4)	Brown (7.5YR 4/4)	Clay loam
V-1	Onion Camp, Oregon	Sec. 29, T.33S., R.9W.	A	0-12	Dark reddish brown (5YR 3/3)	Reddish brown (5YR 4/4)	Gravelly clay loam
VI-1	Bain Station, Oregon	SW¼, NE¼, Sec. 13, T.41S., R.10W.	B	10-30	Dark brown (7.5Y 3/2)	Brown (7.5YR 4/4)	Gravelly clay loam
VII-1	Oregon Mountain, Oregon	NE¼, NE¼, Sec. 17, T.41S., R.9W.	A	0-12	Dark reddish brown (5YR 3/3)	Reddish brown (5YR 4/4)	Gravelly clay loam
VII-2	"	"	B	12-40	Reddish brown (5YR 4/4)	Yellowish red (5YR 4/6)	Gravelly clay loam
VIII-1	Waldo Hill, Oregon	NW¼, SW¼, Sec. 33, T.40S., R.8W.	A	0-15	Dark reddish brown (2.5YR 3/4)	Dark reddish brown (2.5YR 3/4)	Gravelly clay
VIII-2	"	"	B	15-40	Dark reddish brown (2.5YR 3/4)	Dark reddish brown (2.5YR 3/4)	Gravelly clay

Appendix I. (Continued). Serpentine soil sample locations.

Sample No.	Area	Location	Horizon	Depth (cm)	Moist Color	Dry Color	Texture
VIII-3	Waldo Hill, Oregon	NW¼, SW¼, Sec. 33, T.40S., R.8W.	B and C	40+	Dark reddish brown (5YR 3/3)	Reddish brown (5YR 4/3)	Cobbly and gravelly clay
IX-1	Shanks Creek, Oregon	NW, Sec. 20, T.34S., R.5W.	B	10-30	Dark reddish brown (5YR 3/3)	Reddish brown (5YR 4/4)	Gravelly clay loam
X-1	Hunting Creek, California	Sec. 34, T.12N., R.5W.	A	0-10	Dark reddish brown (2.5YR 3/3)	Dusky red (2.5YR 3/2)	Gravelly clay loam
XI-1	Red Mountain, California	NE¼, Sec. 17, T.14N., R.11W.	A	0-10	Dark reddish brown (5YR 3/3)	Reddish brown (5YR 4/3)	Clay loam

Appendix I. (Continued). Serpentine soil sample locations.

Sample No.	Area	Location	Horizon	Depth (cm)	Moist Color	Dry Color	Texture
VIII-3	Waldo Hill, Oregon	NW¼, SW¼, Sec. 33, T.40S., R.8W.	B and C	40+	Dark reddish brown (5YR 3/3)	Reddish brown (5YR 4/3)	Cobbly and gravelly clay
IX-1	Shanks Creek, Oregon	NW, Sec. 20, T.34S., R.5W.	B	10-30	Dark reddish brown (5YR 3/3)	Reddish brown (5YR 4/4)	Gravelly clay loam
X-1	Hunting Creek, California	Sec. 34, T.12N., R.5W.	A	0-10	Dark reddish brown (2.5YR 3/3)	Dusky red (2.5YR 3/3)	Gravelly clay loam
XI-1	Red Mountain, California	NE¼, Sec. 17, T.14N., R.11W.	A	0-10	Dark reddish brown (5YR 3/3)	Reddish brown (5YR 4/3)	Clay loam

Appendix II. List of scientific names of plants mentioned in the text.

Alpine springbeauty	Clatonia megarhiza var. nivalis (English) C. L. Hitche
Blue wildrye	Elymus glaucus Buckl.
Blunt-leaved sandwort	Arenaria obtusiloba (Rydb.) Fern.
Bottlebrush squirreltail	Sitanion jubatum J. G. Sm.
Canyon live oak	Quercus chrysolepis Liebm
Common juniper	Juniperus communis L.
Cypress	Cuppressus sargentii
Digger pine	Pinus sabiniana
Douglas-fir	Pseudotsuga menziesii (Mirb.) Franco
Fescue	Festuca
Geyer oniongrass	Melica geyeri Munro
Incense cedar	Libocedrus decurrens Torr.
Jeffrey pine	Pinus jeffreyi Grev. & Balf.
Knobcone pine	Pinus attenuata Lemm.
Lemmon needlegrass	Stipa lemmonii (vas.) Scribn.
Lodgepole pine	Pinus contorta Dougl.
Manzanita	Arctostaphylos
Mt. Stuart bluegrass	Poa curtifolia Scribn.
Narrow-leaved buckbrush	Ceanothus cuneatus (Hook.) Nutt.
Oarleaf buckwheat	Eriogonum pyrolaefolium Hook, ex A. Murr.
Pine-mat manzanita	Arctostaphylos nevadensis Gray
Podfern	Chelanthes siliquosa Maxon
Scrub oak	Quercus vaccinifolia
Sheep fescue	Festuca ovina L.

Speech feature	Feature value f.
Stop sub	Obstruct articulation
Subject	Substantive attribute noun
Time-out mechanism	Microcomputer breakpoint circ
Vertical punctuation	Exclusive hierarchical mode' ex A. punct.
Walton-Jensen punctuation	Combination conjunct (mode') unit.
WL. Grant pinedrama	Fog classifier scrip.
Wordsworth	Microcomputer
Xoxobook byte	Time controls punct.
Yemmon needlework	Extra locomotive (war.) script.
Zoophone byte	Time actuarial room.
Zaitsev byte	Time function crew. e gait.
Increase count	Liposculpture negotiate fore.
Power curcuit	Motive heart mute
Forces	Instruct
Pongya-jit	Thermometric mountain (mtp.) tavern
Offset byte	Time explosive
Cabinet	Combinatorial earthquake
Common locator	Qualitative chemical f.
Coyote jive ox	Doctrine electrocardiogram
Partnership admiralty	Situation Japanese T. C. ga.
Plant-jensen computer	Scientific optometrist (grp.) term.
Pine article	Climate Cyanide gas().
Alpine apartment	Circuit component law. diagram (Control)

Appendix II. List of mathematic names to bytes mentioned in the text.

Appendix II. (Continued). List of scientific names of plants mentioned in the text.

Snow douglasia	Douglasia nivalis Lindl.
Subalpine fir	Abies lasiocarpa (Hook.) Nutt.
Sugar pine	Pinus lambertiana Dougl.
Western white pine	Pinus monticola Dougl.
Whitebark pine	Pinus albicaulis Engelm.

ANNOTATED BIBLIOGRAPHY

Arimura, S. and I. Kanno. 1965. Genesis and characteristics of Brown Forest soils derived from serpentine in Kyushu, Japan. Part 4. Micropedological Features. Soil Science and Plant Nutrition 11:235-240.

The A horizon is characterized by a weakly developed spongy porphyritic (or porphyropeptic) fabric, and the B by porphyritic fabric. The porosity of these soils decreases with depth. The oriented clays occurring in the B horizons indicate the presence of illimerization. The creeping nature of the deposit on mountain slopes is indicated by the fluidal structure in the B horizons.

Berry, L. G. and B. Mason. 1959. Mineralogy, concepts, descriptions, determinations. W. H. Freeman and Company. Pages 506-507. Library of Congress Catalog Card Number 59-7841.

Serpentine ($Si_4Mg_6O_{10}(OH)_8$) is trioctahedral 1:1 phyllosilicate. The authors classify serpentine group minerals into antigorite (platy, analogue to kaolinite) and chrysotile (fibrous, analogue to halloysite). The iron present in some serpentine minerals results from the replacement of Mg by Fe and some Al probably through substitution for Mg in octrahedral and Si in tetrehedral positions. Nickel-bearing variety of serpentine is called garnierite and is apple-green in color.

Birrell, K. S. and A. C. S. Wright. 1945. A serpentine soil in New Caledonia. New Zealand Jour. Sci. Tech. 27A:72-76.

The soils have very low contents of SiO_2 (in the order of 3-13%), especially in the upper horizons. The soils are high in Fe_2O_3 (in the order of 60%). The soils are low in N, P, and exchangeable bases, and contain high amounts of exchangeable chromium and nickel. The soil forming process is lateritic. High amounts of chromium and nickel are listed as probable causes for the absence of common tropical vegetation. The authors indicate that the species which have established themselves on the serpentine have developed sufficient tolerance to the elements (Cr and Ni).

Bogatyrev, K. P. 1958. "Smolnitzy" (Smonitsa) of Albania (Cinnamon-Brown Meadow and Meadow Cinnamon-Brown Dark-colored magnesium Solonetz-like Soils). [Pochvovedeniye No. 4, 14 (English translation 358-364)].

Magnesium is the predominant cation in the adsorbing complex which imparts some salinity properties to these soils. Although nontronite present in these soils imparts unfavorable properties, these unfavorable properties are enhanced by Mg.

Brindley, G. W. 1961. Kaolin, serpentine, and kindered minerals. In: The X-ray identification and crystal structures of clay minerals. G. Brown (Ed.). Mineralogical Society, 41 Queen's Gate, London. p. 51-131.

The author discusses classification, nomenclature, morphology, effect of heat, and identification of serpentine minerals. The following summary on lattice parameters of serpentine minerals is taken from this article.

Lattice parameters of serpentine minerals.

Mineral	a, Å	b, Å	c, Å	β
Chrysotile (clino)	5.34*	9.20	14.6	93° 12'
Chrysotile (ortho)	5.34*	9.20	14.6	90°
1-layer ortho-serpentine (lizardite)	5.31	9.20	7.31	90°
6-layer ortho-serpentine	5.32	9.22	43.6	90°
Antigorites	33.7 35.5 38.3 41.1 43.1 91 109	9.26	7.28	91° 24'

* There is some uncertainty as to whether these values are 5.34 or 5.32 Å. Whittaker and Zussman (1956) mention both values.

Brindley, G. W. and F. H. Gillery. 1954. Mixed-layer kaolin-chlorite structure. Clays and Clay Minerals. p. 349-353. (A. Swineford and N. Plummer, Editors). Publication 327, Nat. Acad. Sci. - Nat. Res. Coun., Washington.

The authors show the relationship between trioctahedral chlorite and serpentine structure. Serpentine structure results from removal of silica tetrahedral layer from trioctahedral chlorite.

Burgy, R. H. 1970. Evaluation of water yield potential in East Putah Creek Watershed under multiple use management. Report to U. S. Department of Interior, Bureau of Land Management and Bureau of Reclamation. Department of Water Science and Engineering, University of California, Davis, California.

The author reported pH values greater than 8 as well as pH values between 6 and 7 for soils over serpentine rock. Careful examination of Burgy's report indicated that soils with high pH values are developed from mixed parent materials of serpentine and diabase. The author also gives data on exchangeable cations of serpentine soils. It is noted that percentage saturation of CEC with Ca is low, whereas with Mg, it is high. The calcium to magnesium ratio is low.

Butler, J. R. 1953. The geochemistry and mineralogy of rock weathering (1) The Lizard Area, Cornwall. Geochim. et Cosmochim. Acta 4:157-178.

The analyses of tremolite-serpentine rock (chrysotile and antigorite (60-70%), chlorite (10-15%), tremolite (5-10%) and small amounts of magnetite, chromite, olivine and enstatite) and of the silt and clay fractions in the weathered material immediately above the rock, show clearly that Si and Mg are lost, while Fe is gained relative to Al in the sequence rock → silt → clay. The predominant clay fraction is chlorite (70%), with some illite and small amounts of kaolin, montmorillonoid, and talc. The ratio of Mg/Ni decreases on weathering.

Clark, S. C. and P. F. Holt. 1960. Dissolution of chrysotile asbestos in water, acid and alkali. Nature 185:237.

The magnesium ions are leached from the chrysotile. The two dimensional sheets of silicon-oxygen lattice which are left behind are resistant to water except at elevated temperatures. The sodium hydroxide (0.1 N) scarcely attacks chrysotile unless the protective layer of hydrated magnesium ions is first removed by acid. The chrysotile is highly weatherable under alternating acid and alkaline conditions.

Coombe, D. E. and L. C. Frost. 1956a. The heaths of the Cornish serpentine. Journal of Ecology 44:226-256.

The authors describe four major heath types in the area.

(1) "Rock Heath" (Festuca ovina - Calluna heath) in shallow soil pockets among serpentine rocks. The soil is 'Brown Ranker'.
(2) "Mixed Heath" (Erica vagans - Ulex europaeus heath) in deep soil (20-40 cm). The soil is 'Eutrophic Braunerde'.
(3) "Tall Heath" (Erica vagans - Schoenus heath) in shallow valleys and depressions. The soil is deep and is called 'Anmoor'.
(4) "Short Heath" (Agrostis setacea heath). The soils are deep silty fine sand overlying serpentine. The soils are called as 'Pseudogley'.

Coombe, D. E. and L. C. Frost. 1956b. The nature and origin of the soils over the Cornish serpentine. Journal of Ecology 44:605-615.

The soils developed almost wholly from serpentine are classified as "Brown Ranker" and "Eutrophic Braunerde". Brown Ranker is shallower

and under "rock heath" (Festuca ovina - Calluna heath). "Eutrophic Braunerde" is commonly 20-40 cm deep, but shallower in rock pockets and is under mixed heath (Erica vagans - Ulex europaeus heath). The other types of soils in the area are "Pseudogley" (short heath - Agrostis setacea heath) with incipient podsolization, developed in a fine-sandy deposit of foreign origin and "Anmoor" (Tall heath-Erica vagans - Schoenus heath) partly derived from serpentine, partly derived from foreign material.

Cowan, D. S. and C. F. Mansfield. 1970. Serpentine flows on Joaquin Ridge, Southern Coast Ranges, California. Geological Society of America Bulletin 81:2615-2628.

The serpentinite flows are similar in their external form to solidified lava flows and debris flow deposits. The serpentine flows (similar to serpentinite rock) consist of rounded blocks (about 4 meters) of parent serpentinized rock enclosed in a matrix of flaky, intensely sheared serpentine which act as weak points in the rock mass. The calculated shear strength values are very low which indicate that the tubular masses of sheared serpentinite found in the region could have been tectonically emplaced in the upper parts of the crust at low temperatures and under modest stresses.

Crooke, W. M. 1956. Effect of soil reaction on uptake of nickel from a serpentine soil. Soil Science 81:269-276.

The reduction in toxicity symptoms (oats) and Ni absorption depends on a reduction in available Ni due to change in soil pH, rather than on the improved Ca status of the soil due to $CaCO_3$ applications.

Deer, W. A., R. A. Howie, and L. C. Frost. 1962. Rock forming minerals. Vol. 3. Sheet silicates. New York: John Wiley and Sons, Inc.

The serpentine mineral has been assumed to have different forms but the same composition. These polymorphs were considered to be trioctrahedral analogue of the kaolin group minerals. The above authors believe that antigorite is not a true polymorph because it differs from chrysotile and lizardite both in structure and composition.

Franklin, J. F. and C. T. Dyrness. 1969. Vegetation of Oregon and Washington. U.S.D.A. Forest Service Research Paper PNW-80, 216 pp., Illustrated. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

The authors describe general vegetation on serpentine rocks and soils in Oregon and Washington.

Frasche, D. F. 1941. Origin of the Sunigao iron ores. Economic Geology 36:280-305.

The iron ore in Suniga (Philippines) is lateritic in origin, having been derived by a process of subaerial decomposition of the parent serpentine rock. The weathering of serpentine was accompanied by rapid losses of the more soluble constituents like Si and Mg and gains of less soluble components like aluminum, iron, chromium, nickel and cobalt. The laterites are the result of katamorphic alteration of serpentine.

Gordon, A. and C. B. Lipman. 1926. Why are serpentine and other magnesian soils infertile? Soil Science 22:291-302.

The soils are low in N,P,K especially N and P, and have high pH values. The experiments with barley indicated that high pH and low available amounts of major nutrients, especially N and P rather than high Mg content were the main causes of infertility of these soils.

Halsted, R. L. 1968. Effect of different amendments on yield and composition of oats grown on a soil derived from serpentine material. Canadian Journal of Soil Science 48:301-305.

The author observed the effects of additions of $Ca(OH)_2$, organic matter, and $CaSO_4$ on the yield of oats grown on serpentine soil. Additions of $Ca(OH)_2$ and organic matter increased oat yields several times and was accompanied by increases in available calcium and decreases in available Ni of soils and increase in Ca and decrease in Ni content of plants. $CaSO_4$ increased the available calcium status of soils but had little effect on yield. The authors conclude that the increase in pH due to addition of $Ca(OH)_2$ and the chelating effect of organic matter were effective in reducing Ni toxicity thereby increasing yield.

Harshberger, J. W. 1903. The flora of the serpentine barrens of southeast Pennsylvania. Science, N.S. 18:339-343.

Outcrops of serpentine rock are present in parts of Montgomery, Delaware, Chester and Lancaster counties of Pennsylvania. The soils are shallow, the flora is barren in appearance, and the types of flora differ sharply from the surrounding nonserpentine areas. The author indicates that the physical conditions of the soil (edaphic conditions) play a more important part in supporting characteristic flora on serpentine soils than the chemical character of the soil.

Hotz, P. E. 1964. Nickeliferous laterites in Southwestern Oregon and Northwestern California. Economic Geology 59:355-396.

The laterites are derived by weathering of the ultramafic rocks. The predominant secondary mineral formed is goethite with minor amounts of

montmorillonite, chlorite and talc. The lateritic soils are similar to soils formed by lateritic weathering of ultramafic rocks in Cuba, Phillippines, New Caledonia, and other tropical regions, although they are higher in Si and Mg and lower in Fe_2O_3 than deposits formed in tropical climates.

Hoyos De Castro, A. 1960. La Genese Du Sol Sur Roches Basiques. Transactions of 7th International Congress of Soil Science. Madison, Wisconsin. 4:413-417 (English summary).

The thin sections showed the alteration of olivine to serpentine in rocks. There is a loss of Mg and Si in soils; this loss is larger in the clay fraction in which serpentine partly alters to vermiculite and chlorite.

Hunter, J. G. and O. Vergnano. 1952. Nickel toxicity in plants. Ann. Appl. Biol. 39:279-284.

The serpentine soils are low in P and K, satisfactory in Ca, and high in Mg and Ni. The Ni content of soils (exchangeable Ni 22-61 ppm) and plants (17-134 ppm Ni in oat leaves) is very high. The normal exchangeable soil content of Ni is 0.2 ppm and total content of Ni in normal oat leaves is 3 ppm. The nickel toxicity is shown by many plants. $CaCO_3$ and $CaSO_4$ were used to study the effect of Ca and pH on nickel toxicity symptoms. It was shown that the beneficial effect (correcting deficiency symptoms of nickel) of $CaCO_3$ is not because of increase in exchangeable Ca but because of increase in pH. The nickel toxicity is increased when the Ca, Mg, N, or K supply is low or when the P supply is high.

Ishimoto, T. T. 1958. Systematic considerations as influenced by certain ecological factors related to plant distribution on serpentine soil in Central California. Ph.D. Thesis, Oregon State College.

The author compared the chemical composition of serpentine and nonserpentine soils. The serpentine soils mostly contained greater quantities of N(0.06 to 0.11%), P(0.03 to 0.11 me/100 g), and K (0.64 to 0.77 me/100 g) than nonserpentine soils. The Ca to Mg ratio of serpentine soils was less than one, whereas that of nonserpentine soils was greater than one. Micronutrient analysis is not given. Helianthus bolanderi ssp. exilis was the only serpentine endemic species found in the area. Clones of Stipa pulchra from serpentine soil were transplanted on to the serpentine and nonserpentine soil and clones of above species from nonserpentine soil were also transplanted on to both types of soils. The results showed that the serpentine strain is better adapted to serpentine soil than to nonserpentine soil. Seeds of Helianthus annuus collected from plants on two types of soils when planted in a similar manner to clone transplants differentiated into serpentine intolerant and serpentine tolerant species. To explain the peculiarities of serpentine flora, the author suggests the physiological approach should be followed.

Joffe, J. S. and M. Zimmerman, 1944. Sodium, calcium, and magnesium ratios in the exchange complex. Soil Science Society of America Proceedings 9:51-55.

Soils with low Ca:Mg ratio behave similarly in their physical properties to the soils with high Na content. A high Ca:Mg ratio (11:1) is far more effective in reducing the swelling caused by Na than is a low Ca:Mg ratio (1:1.25). Narrowing of the Ca:Mg ratio decreases the moisture absorption; Mg concentration reduces dispersion in the presence of Na and increases it in the absence of Na. Poor yields of sudan grass (tops and roots) are obtained from soils with low Ca:Mg ratio.

Johnson, C. M., G. A. Pearson, and P. R. Stout. 1952. Molybdenum nutrition of crop plants. II. Plant and soil factors concerned with molybdenum deficiencies in crop plants. Plant and Soil 4: 178-196.

Thirty crop species were grown on serpentine soil fertilized with Ca, N, P, and K. The grasses (barley, oats, and wheat) and legumes (cow peas, and beans) did not show any molybdenum deficiency whereas other species (18) showed molybdenum deficiency symptoms, which were corrected on application of molybdenum. Factors (chemical, geological, and weathering) in relation to the development of the low available molybdenum of serpentine soils are discussed.

Kanno, I., S. Tokudome, S. Arimura, and Y. Onikura. 1965. Genesis and characteristics of Brown Forest soils derived from serpentine in Kyushu, Japan. Part 2. Genesis and characteristics of brown forest soils. Soil Science and Plant Nutrition 11:141-150.

The vegetation on soils derived from serpentine in Kumamoto prefecture consists of poor stand of Pinus thunbergii with an undergrowth of Cheialamthes brandtii, Smelix china, Arundinaria simoni and bushes of Fagaceae. As the weathering of the parent rocks proceeded, the Mg and silica were lost from the solum, whereas the iron oxides accumulated. The soils are characterized by neutral reactions and extremely high base status, especially a high-Mg saturation (about 70%). The soils are classified as Brown Forest soils. (Gives chemical analysis of soils and parent rock).

Kanno, I., Y. Onikura, and S. Tokudome. 1965. Genesis and characteristics of Brown Forest soils derived from serpentine in Kyushu, Japan. Part 3. Clay mineralogical characteristics. Soil Science and Plant Nutrition 11:225-234.

Under subtropical humid conditions, the lower the degree of serpentinization, the more the formation of layer lattice silicate other than serpentine minerals (predominance of 14 Å and 7° minerals). The soils are dominated by antigorite and 14 Å minerals mainly of randomly interstratified chlorite/Al-vermiculite. In addition to above minerals, varying amounts

of chrysotile, expanding minerals, iron oxides, talc, and quartz are found. The soil material of the A horizons contains much more less-weathered materials of serpentine than does that of the B horizons.

Kruckeberg, A. R. 1951. Intraspecific variability in the response of certain native plant species to serpentine soil. Amer. Jour. Bot. 38:408-419.

Some strains of species Streptanthus glandulosus collected from nonserpentine localities showed intolerance to serpentine. The strains of some species from serpentine sites retained normal growth on serpentine soil. This suggested the "biotype depletion" as one possible mode of origin of serpentine endemics. As shown for above species, Gilia capitata and Achillea borealis (non endemic) can be separated into serpentine tolerant and serpentine intolerant races on the basis of their growth responses on serpentine soil. When these soil races are viewed from biosystematic standpoint, they can be called edaphic ecotypes.

Kruckeberg, A. R. 1954. The ecology of serpentine soils. III. Plant species in relation to serpentine soils. Ecology 35:267-274.

The important requirement for existence of serpentine endemics on serpentine soil is their capacity to obtain calcium at low levels. The species which grow in both serpentine and non serpentine soils do so because their population is specially adapted to low levels of calcium. In addition to the above, the serpentine plants should be adapted to low levels of nutrients, to openness and strong exposure to evaporation, to adverse physical properties of soils, and to other factors. Streptanthus glandulosus Hook, indicating two types of endemism ('biotype depletion' and 'insular', proposed by Stebbins, 1942) is the most widespread serpentine species of the genus Streptanthus in California. The authors showed that serpentine endemic plants may be restricted to serpentine by intolerance of the more rigorous competition in non-serpentine plant species.

Lipman, C. B. 1926. Bacterial flora of serpentine soils. Journal of Bacteriology 12:315-318.

Serpentine soils from the Mount Dialbo region in California contain a very small micro-organic population. The micro-organism population consists mainly of nonchromogenic bacterial forms, very few fungi, actinomyces, and azotobactor (only in one of the three soils). There is an absence of nitrifying bacteria. The author indicates that the absence of microbial population may be the cause of poor nutritional status of (especially of N and P) serpentine soils.

Malquori, A. and S. Cecconi. 1956. Minerali argillosi di terreni provenienti da rocce ofiolitiche. Ricerca Sci. 26:1154.

Several of the soils weathered from serpentine parent materials contained trioctahedral montmorillonite, iron hydroxide, and residual serpentine in the clay fraction. Other soils developed from serpentine materials contained chlorite, swelling chlorite, or chloritized montmorillonite, the total percentage of clay in the soils is small (average around 10%).

Martin, W. E., J. Vlamis, and N. W. Stice. 1953. Field correction of calcium deficiency on a serpentine soil. Agronomy Journal 45: 204-208.

The effectiveness of massive gypsum applications (1,2,4, and 8 tons) on yield of hay and correcting infertility of serpentine soils due to low calcium saturation has been tested. The results indicate that the yield of hay is a direct function of calcium saturation. The calcium saturation (as percent of total cations) of soil was 8. The yield of hay increased several times with increase in Ca saturation to about 18.

McMillan, C. 1956. The edaphic restrictions of Cupressus and Pinus in the coast ranges of Central California. Ecological Monographs 26:177-212.

Plant species from one area were grown on acid soil, serpentine soil and control. All these species showed varying responses to different soils. Pinus bolanderi grew best on acid soil, Cupressus pygmaea on control soil and Agrostis halli grew good on all soils. "These studies strongly suggest that the plant community is the result of the overlapping tolerance ranges of the component individuals for environmental conditions presented by the particular habitat". The hypothesis 'restriction of certain species to two different habitats depends upon the possible presence of a common restrictive factor' was found to be untenable. The physiological differentiation was shown to be present in many species which helps to understand the distribution of these species.

Minguzzi, C. and O. Vergnano. 1953. II. Contenuto di elementi inorganici delle piante della formazione ofiolitica dell Impruneta (Firenze) (English summary) Nuovo Giornale Botanico Italiano N.S.60:287-319.

The soils are high in Mg and low in N. Iron may be deficient because of its non-availability to plants. The authors showed that the main cause of infertility of serpentine soils is the presence of micronutrients such as Ni, Cr, and Co in high amounts and their uptake by plants must be influenced by the nature of plants and major nutrient composition of soil.

Moser, F. 1933. The calcium-magnesium ratio in soils and its relation to crop growth. Journal of American Society of Agronomy 25: 365-377.

The significant factor in determining the crop yields was the amount of active calcium in a soil. Crop yields were increased substantially when the calcium saturation of soil was increased to about 15. No significant correlation existed between exchangeable Ca:Mg ratio and crop yields (Ca to Mg ratios varied from 1:1 to 4.50:1).

Nagatsuka, S. 1965. Genesis of a soil derived from serpentine in Mikkabi-cho, Shizuoka Prefecture (Part 1). Journal of the Science of Soil and Manure, Japan 36:235-239.

The soils are reddish brown in color and high in clay content. The magnetite being a stable mineral, stays as weathering residue, whereas antigorite weathers. The iron and aluminum contents are very high in the fine soil and in citrate-dithionite extracts. This shows allitic type of weathering of soils. Magnesium is the dominant exchangeable cation. The base saturation of the soil is very high (85-100%) and the soils are slightly acid or neutral in reaction.

Nagatsuka, S. 1967. Genesis of a soil derived from serpentine in Makkabi-Cho Shizuoka Prefecture (Part 2). Journal of the Science of Soil and Manure, Japan 38:187-192.

The weathering sequence of antigorite in humid and subtropical environments was deduced as follows: Antigorite → expansible 14 Å mineral → randomly interstratified chlorite - Al vermiculite → chlorite. Kaolin minerals were absent from these soils. This soil is considered to be a member of the Red-Yellow soils.

Novak, F. A. 1928. Quelgues remargues relatines au probliene de la vegetation sur les terrains serpentinigues. Preslia 6:42-71.

The author has reviewed the European literature on serpentine soils. The literature indicates that Ca-Mg ratio is of considerable importance in determining infertility of serpentine soils.

Page, N. J. 1968. Chemical differences among the serpentine "Polymorphs". American Mineralogist 53:201-215.

The chemical compositions of antigorite (relatively low H_2O and high SiO_2), chrysotile (relatively high H_2O and MgO, and small ratio of Fe_2O_3 to FeO), and lizardite (high SiO_2 and low FeO) are different suggesting that these are not polymorphs.

Pichi-Sermolli, R. 1948. Flora e vegetazione delle serpentine e delle altre ofioliti del 'alta valle del Tevere Toscane. (English Summary). Webbia 6:1-380.

The author recognizes the following six tendencies in plants grown on serpentine soils: (1) reduction in size of leaves and other organs,

(2) shrubbiness of growth, (3) stunting or dwarfing, (4) greater development of the root system, (5) increased glaucousness, and (6) reduced pubescence (there are some contrary indications also).

Robinson, W. O., G. Edgington and H. B. Byers. 1935. Chemical studies of infertile soils derived from rocks high in magnesium and generally high in chromium and nickel. U. S. Dept. Agr. Tech. Bull. 471.

The magnesium content is reduced by weathering and soils have much lower contents than rocks. Some serpentine rocks are too low in alumina to form sufficient clay for the establishment of a normal soil covering regardless of the topography. The authors found no physical characteristic which would render serpentine soils particularly unfavorable for plant growth. The presence of large contents of chromium and nickel, and perhaps cobalt, are the dominant causes of infertility of serpentine soils under consideration.

Rune, O. 1953. Plant life on serpentines and related rocks in the north of Sweden. Acta Phytogeographica Suecica 31:1-139.

The author gives an exhaustive list of plants on serpentine soils in North Sweden and general vegetation of serpentine soils of Finland, Norway, North America and East Asia. He divided plants occurring on serpentine soils into following three categories: (1) Serpentine characteristic plants (Serpentinicolous), (2) Serpentine indifferent plants, and (3) Serpentine accidental plants. He lists following six general characteristics of serpentine flora: (1) poor in individuals and species, (2) ecotypes of several species differ ecologically and morphologically (3) disjunctive nature of plants on serpentine localities, (4) contains acidicolous and basicolous plants, (5) relatively xerophytic character, and (6) dominated by certain families or genera e.g. Caryophyllaceae in N. Europe and E. North America. The author indicates that high contents of chronium and nickel are general and dominant causes of infertility of serpentine soils. The total effect of these elements on plant growth in these soils, however, would depend upon the following factors: (1) low nutrient contents, (2) absence of Ca, (3) high magnesium content, (4) presence of iron (reduced form), (5) pH value, and (6) mechanical composition of soils.

Sasaki, S., T. Matsuno, and Y. Kondo. 1968. A podzol derived from serpentine rocks in Hokkaido, Japan. Soil Science and Plant Nutrition 14:99-109.

The mean annual temperature is about 43^{o} F and the annual precipitation is about 120 cm. The A horizon is enriched by SiO_2 and the B horizon by Fe_2O_3. The differentiation of horizons is clear. But the values of pH and base saturation are higher than those of common podzols. The characteristic nature of the soils is the presence of trioctehedral minerals and absence of dioctahedral minerals (kaolinite, halloysite).

Hence, the authors assume that the weathering of clay in this soil progressed only to an intermediate stage.

Spence, D. H. N. 1957. Studies on the vegetation of Shetland. I. The serpentine debris vegetation in Unst. Journal of Ecology 45:917-945.

Most of the serpentine outcrops are covered with closed vegetation with large areas of sparsely colonized scabland. The infertility of serpentine soils in the area is thought to be due to high nickel content (Agrostis stonifera contains 90-118 ppm of dry matter), wind, soil instability, and rapid weathering. High chromium contents may also be involved.

Stebbins, G. L., Jr. 1942. The genetic approach to problems of rare and endemic species. Madrono 6:241-272.

The author defined an endemic plant as "...one poor in biotypes and with its biotypes so specialized that they can grow and compete with other species in only a limited area." He proposed the following types of endemics: (1) "depletion" (the endemic status acquired by the species through loss of most of its biotypes which formerly allowed the species to exploit a greater variety of habitats) and (2) "insular" (originated from isolated individuals pre-adapted to a specific habitat situation).

Tadros, T. M. 1957. Evidence of the presence of an edapho-biotic factor in the problem or serpentine tolerance. Ecology 38:14-23.

Emmenanthe Penduliflora (nonserpentine herb) and Emmenanthe rosea (Serpentine herb) were grown on serpentine and nonserpentine soils and in sand cultures. E. rosea showed more tolerance to high Mg and to deficiency of Ca, K, and P. The rate of survival of E. rosea was low when it was grown on nonsterilized garden soil as compared to one type of serpentine soil Henneke series). E. rosea was more tolerant than E. Penduliflora when the above soils were sterilized. The best survival rate and growth response of E. rosea was obtained on sterilized serpentine (Montana series) and garden soil. This indicated the presence of biotic factor (soil microorganisms) that hinders the establishment of the seedlings of the presumed serpentine tolerant taxon on more fertile soils.

Usov, N. I. 1937. Effect of absorbed magnesium on saline properties of soil. Proc. Conf. Soil Sci., Saratov 1, 44-61 (In: Chemical Abstracts 33:8342-9, 1939).

With a Ca:Mg ratio of more than 2:1, the physical properties of the soil are determined by its Ca content. With more than 40% of the

total CEC satisfied by Mg, the soil aquires saline properties such as increased hygroscopicity, dispersion, swelling capacity, coloration of filtrate and diminished permeability to water. The effect of Mg on these properties is far smaller degree than that with Na.

U.S.D.A. 1963. Soil Survey of Chester and Delaware Counties. Pennsylvania Series 1959, No. 19. Washington, D. C., Soil Conservation Service.

Predominant clay mineral is similar to montmorillonite. The soils are >50% Mg saturated. The dominant soil series in the counties is Chrome. The natural vegetation is white oak, red oak, and black oak, with stunted cedar and dwarfed white pine. The soils are known as "the Barrens" and are moderately sloping. Where topography allows, the soils are best suited to hay and pasture rather than farm crops.

Venaile, F. and H. W. Van der Marel. 1963. An interstratified saponite-swelling chlorite mineral as a weathering product of lizardite rock from St. Margherita staffora (Pavia Province), Italy. Beit, Mer al. Petrog. 9:198-245.

There is a relative increase in sesquioxides and decrease in silica and Mg as weathering proceeds from rock → silt → clay. The chlorite showed increasing trends with depth in profile clay samples, whereas swelling chlorite and saponite showed decreasing trend with depth.

Vergnano, O. 1953a. L'azione fisiologica del nichel sulle piante di un terreno serpentinoso. (English Summary). Nuovo Giornale Botanico Italiano N.S.60:109-183.

The main cause of infertility of serpentine soils in Whitecairns, Aberdeenshire, Scotland, was attributed to high nickel content. The nutritional status of soils and plant effects the toxicity of nickel on plant growth. Toxicity of nickel is high when N, Ca, Mg or K is in low concentration and when P is high.

Vergnano, O. 1953b. Effectti di alte concentrazioni di nichel su alcune piante da culture. (English Summary). Nuovo Giornale Botanico Italiano N.S.60:189-196.

The effects of high nickel concentrations were observed on many crop plants. It was found that barley was most resistant while beets were least resistant to high nickel concentrations. The symptoms of nickel toxicity using 2.5 ppm Ni solution were similar to those observed on serpentine soils.

Vlamis, J. and H. Jenny, 1948. Calcium deficiency in serpentine soils as revealed by absorbent technique. Science 107:549.

Additions of N,P,K enhanced the growth of Romaine lettuce significantly indicating that the serpentine soils are deficient in these elements. The contents of Cr, Ni, and Co as disease (lettuce rosette) producing agents is ruled out. The low degree of saturation of exchangeable calcium is a prime contributing factor in the origin of lettuce rosette.

Vlamis, J. 1949. Growth of lettuce and barley as influenced by degree of calcium saturation of soil. Soil Science 67:453-466.

The serpentine soils showed a severe deficiency of N and P and a slight deficiency of K as revealed by growing barley and lettuce on these soils. The soils are low in Ca. The degree of saturation of soil with Ca is an important factor in controlling the lettuce rosette disease rather than the Ca to Mg ratio. Optimum yields of barley and lettuce were obtained with about 20% calcium saturation.

Wagner, N. S. and Len Ramp. 1958. Occurrences of Peridotite-Serpentine in Oregon. The Ore Bin 20:13-20.

A rough estimation of peridotite-serpentine rock in Oregon (from maps given by authors) indicates that about 450 square miles of Oregon's area is occupied by this rock. Lateritic process of soil formation is observed in Southwestern Oregon. The soils are very low in Si and high in Al, Fe, and chromium as compared to the rock.

Walker, R. B. 1948. Molybdenum deficiency in serpentine barren soils. Science 108:473-475.

The serpentine soils are slightly acidic and predominant exchangeable cation on the base exchange complex is Mg ($\frac{Ca}{Mg}$ = 0.1 to 0.3). Tomato plants responded to Ca applications. Tomato and Romaine lettuce showed deficiency symptoms of molybdenum, which were corrected only by the application of molybdenum. This shows that serpentine soils are low or deficient in available molybdenum in addition to calcium.

Walker, R. B. 1954. The ecology of serpentine soils. II. Factors affecting plant growth on serpentine soils. Ecology 35:259-266.

The low contents of total and adsorbed calcium is the basic cause of infertility of serpentine soils. The various unfavorable physical factors, low levels of major nutrient elements (especially N and P), alkalinity, low available molybdenum and high levels of nickel and chromium are of secondary importance in controlling the vegetation of serpentine soils. The plants that grow well on serpentine soils must first be tolerant of low calcium levels and, in addition, must be tolerant to other secondary factors mentioned above.

Walker, R. B., H. M. Walker, and P. R. Ashworth. 1955. Calcium-magnesium nutrition with special reference to serpentine soils.

Plant Physiology 30:214-221.

There was a marked decrease in yield of crop plants at exchangeable Ca levels of 20% or less and very little growth was shown at levels less than 10%. The yields of native plants (serpentine endemics) was not affected by Ca levels (6-82%). The native plants absorbed more Ca and less Mg at the lower levels of exchangeable Ca (3-15%) than crop plants. This indicates that native serpentine species do not have lower requirements for Ca but they are able to absorb more Ca than crop plants from a Ca deficient soil.

Waring, R. H. 1969. Forest plants of the Eastern Siskiyous: Their environmental and vegetational distribution. Northwest Science 43:1-17.

The author describes the vegetation on soils derived from peridotite or serpentine as Jeffrey pine (Pinus Jeffreyi) type. White fir and western white pine are stand components at higher elevations. Incense cedar and Douglas-fir are generally present at all elevations. Mountain hemlock and Shasta red fir are absent. Lupinus leucophyllus, Xerophyllum tenax, and Arctostaphylos nevadensis occur on more moist and cooler sites. Silene companulata, Garrya fremontii, Onychium densium, Astragalus whitneyi, Quercus Vaccinifolia, Arenaria nutallii, and Frasera albicarlis occur on drier sites.

Wells, P. V. 1962. Vegetation in relation to geological substratum and fire in the San Luis Obispo quadrangel, California. Ecological Monographs 32:79-103.

The weathering of serpentine produced beidellite clay. The local serpentine soils are mapped as Montana series. Cupressus sargentii occurs only on serpentine indicating segregation of the species. On the other hand, serpentine oak (Quercus durata) and serpentine manzanita (Archtostaphylos obispoensis) were also found on diabase. "...Fire accentuates the differences in substratum by destroying the forest canopy and opening the way for vegetation of more diverse physiognomy, with grasslands on the deeper, zonal soils, and shrublands on the lithosols and regosols..."

Whittaker, R. H. 1954a. The ecology of serpentine soils. I. Introduction. Ecology 35:258-259.

The author mentions the serpentine areas of the world and points out that serpentine areas have many common characteristics such as sterile and unproductive soils, and narrowly endemic species in contrast with that on other soils.

Whittaker, R. H. 1954b. The ecology of serpentine soils. IV. The vegetational response to serpentine soils. Ecology 35:275-288.

The vegetation on serpentine and quartz diorite in the Siskiyou Mountains of Southwestern Oregon differ. The serpentine vegetation appears in general to be characterized by apparent xeromorphism, and the serpentine flora is more restricted in average extent and has its greatest extent toward the south in contrast to diorite flora. The open stunted stands of pines, sclerophyllous shrubs and grass, and numerous endemic species characterize the serpentine flora, where diorite vegetation is characterized by closed Douglas-fir - schlerophyll forests.

Whittaker, R. H. 1960. Vegetation of the Siskiyou Mountains, Oregon and California. Ecological Monographs 30:279-338.

"...Low-elevation vegetation gradates from still more open Chamaecyparis-Pinus monticola-Pseudostuga mesic stands, through very distinctive forest shrub stands with several conifers and two-phase undergrowth of sclerophyll shrubs and grasses, to Pinus jeffreyi woodlands... ...The serpentine flora has a much higher representation of endemics, smaller average extent in all directions, but stronger southern affinity than the diorite vegetation... ...Some Siskiyou species show evidence of population bimodality in relation to the topographic moisture gradient or elevation. Most species show "shift toward the mesic," or displacement of their distribution toward less xeric sites, from diorite to gabbro to serpentine."

Whittaker, E. J. W. and J. Zussman. 1956. The characterization of serpentine minerals by X-ray diffraction. Mineralogical Magazine 31:107-126.

These authors classify serpentine minerals as follows:

Serpentine minerals → Antigorite
Serpentine minerals → Lizardite (one layer orthostructure)
Serpentine minerals → Chrysotile (tubular) → Orthochrysotile
Serpentine minerals → Chrysotile (tubular) → Clinochrysotile
Serpentine minerals → Chrysotile (tubular) → Parachrysotile

Wildman, W. E. 1967. Serpentinite weathering and clay mineral formation in some California soils. Ph.D. Thesis. Davis, University of California. 167 numbered leaves.

The author has reviewed some of the literature on weathering of serpentine soils. He reports that tropical weathering products of serpentinite rocks are very high in iron oxides. Nontronitic montmorillonite with small amounts of residual serpentine are the only minerals identified by X-ray diffraction in clay fractions of soils developed from serpentinite in serveal areas in California. Dissolution studies on serpentinite parent rock with various concentrations of CO_2 solutions for various time periods indicated that Si and Mg dissolved more rapidly in high-CO_2 solutions. The stability relations of serpentine, brucite, gibbsite and amorphous $Fe(OH)_3$ indicates that hydroxy Al and Fe are more likely to nucleate montmorillonites than hydroxy-magnesium. This helps to explain the presence of nontronitic rather than saponitic montmorillonites in California serpentinite soils.

Wildman, W. E., M. L. Jackson, and L. D. Whittig. 1968a. Serpentine rock dissolution as a function of CO_2 pressure in aqueous solution. American Mineralogist 53:1252-1263.

Suspensions of ground serpentine rock were subjected to various CO_2 partial pressures. Mg and Si dissolved more rapidly, reached higher concentrations and Mg:Si ratio was higher in high CO_2 solutions than in low CO_2 solutions. This suggests that soil water, enriched in CO_2 removes Mg from the system and Fe and Al present as impurities in the serpentine, presumably rearrange to form the octahedral layer of the soil montmorillonite.

Wildman, W. E., M. L. Jackson, and L. D. Whittig. 1968b. Iron-rich montmorillonite formation in soils derived from serpentine. Soil Science Society of America Proceedings 32:787-794.

The predominant exchangeable cation is Mg. The soil clays contrast with the parent serpentine in having higher amounts of SiO_2, Fe_2O_3, and Al_2O_3 and lower amounts of MgO. With the loss of Mg, pedogenic montmorillonite enriched in Si, Fe, and Al was formed.

Wollast, R., F. T. Mackenzie, and O. P. Bricker. 1968. Experimental precipitation and genesis of sepiolite at earth-surface conditions. American Mineralogist 53:1645-1662.

Sepiolite [$Mg_2 Si_3O_8 (OH)_n$] is the only cation-bearing silicate that can precipitate directly from sea water as dissolved silica concentration is increased; the depression of pH of sea water prevents the formation of sepiolite and increases the concentration of Si to increase to saturation with respect to amorphous silica. The following are the most important factors in the genesis of sepiolite: (1) The aquous aluminum species and reactive aluminous solid phases should be absent; if aluminum is present, the Mg will be incorporated into the aluminosilicate structure such as chlorite, and (2) The activities of Mg^{2+}, OH^-, and SiO_2 should be consistant with the equilibrium constant for sepiolite.

Yamanaka, T. 1959. Bull. Fac. Education Kochi University. No. 11: 87. Quoted by Kanno et al. 1965, Soil Science and Plant Nutrition 11:141-150.

The serpentine areas in low elevations of Shikoku and southwestern Honshu are characterized by open and stunted pine forest of Abelieto - Pinetum densiflorae accompanied by a large number of types of lesser vegetation. Although chemical properties of the soils are a major factor in determining the peculiar vegetation on serpentine soils, microclimate, topography, and physical properties of soils also have casual relations to vegetation.

Yatazawa, M. and H. Tanaka. 1965. Levels of available micronutrient metals in some Japanese soils as measured by Aspergillus niger with

special reference to their threshold values. Soil Science and Plant Nutrition 11:157-163.

The serpentine soils are low in available Mo (close to deficient), whereas they are high in Cu and Zn.

Youngberg, C. T. 1964. Soil-site correlation studies. (Illinois Valley Soil Conservation District). Unpublished data. Department of Soils, Oregon State University, Corvallis.

The site index study on soils influenced by serpentinitic materials indicates that the higher the ratio of exchangeable Ca to exchangeable Mg, the higher the site index.

Zussman, J., G. W. Brindley, and J. J. Comer. 1957. Electron diffraction studies of serpentine minerals. American Mineralogist 42:133-153.

These authors classify serpentine minerals as given in the following table.

Classification of serpentine minerals (Zussman, Brindley, and Comer, 1957).

	Chrysotile clino, ortho, para	1-layer ortho-serpentine (lizardite)	6-layer ortho-serpentine		Antigorite, various a-parameters	
Morphology seen in hand specimens	Fibrous; occasionally massive	Massive; platy	Massive; fibrous	Platy	Massive; platy	Fibrous (picrolite)
Morphology seen in the electron microscope; dispersed state	Tubes Laths	Plates	Laths	Plates	Plates	Broad laths